

AD-A148 479

ADVANCED DIAGNOSTICS FOR REACTING FLOWS(U) STANFORD

1/1

UNIV CA HIGH TEMPERATURE GASDYNAMICS LAB

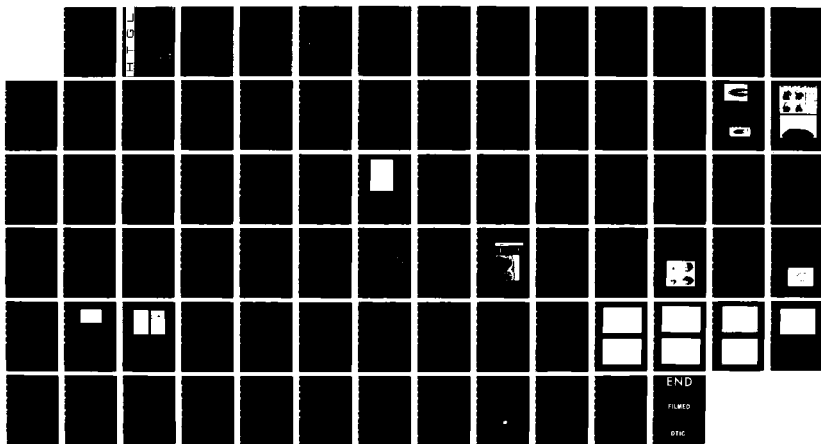
R K HANSON ET AL. NOV 83 AFOSR-TR-84-1072

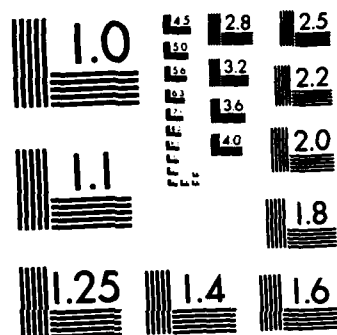
UNCLASSIFIED

F49620-83-K-0004

F/G 20/4

NL





MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

AFOSR-TR- 84 - 1072

①

Annual Scientific Report

on

ADVANCED DIAGNOSTICS FOR REACTING FLOWS

Contract F49620-83-K-0004

AD-A148 479

Prepared for

AIR FORCE OFFICE OF SCIENTIFIC RESEARCH

For the Period

October 1, 1982 to September 30, 1983

Submitted by

R. K. Hanson, Project Director

D. Baganoff

C. T. Bowman

R. L. Byer

B. J. Cantwell

L. Hesselink

S. A. Self

DTIC FILE COPY

DTIC
ELECTE
DEC 1 2 1984
S E D

407079

HIGH TEMPERATURE GASDYNAMICS LABORATORY
Mechanical Engineering Department
Stanford University

Approved for public release;
distribution unlimited.

84 12 03 176

Annual Scientific Report
on
ADVANCED DIAGNOSTICS FOR REACTING FLOWS
Contract F49620-83-K-0004

Prepared for
AIR FORCE OFFICE OF SCIENTIFIC RESEARCH

For the Period
October 1, 1982 to September 30, 1983

Submitted by
R. K. Hanson, Project Director
D. Baganoff
C. T. Bowman
R. L. Byer
B. J. Cantwell
L. Hesselink
S. A. Self

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER AFOSR-TR. 84-1072	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Advanced Diagnostics For Reacting Flows		5. TYPE OF REPORT & PERIOD COVERED Annual Scientific Report 10/1/82 to 9/30/83
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) R. K. Hanson		8. CONTRACT OR GRANT NUMBER(s) F49620-83-K-0004
9. PERFORMING ORGANIZATION NAME AND ADDRESS Stanford University Department of Mechanical Engineering Stanford, California 94305		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 61102F 2308/A3
11. CONTROLLING OFFICE NAME AND ADDRESS Air Force Office of Scientific Research/NA Building 410 Bolling AFB, D. C. 20332 - 6448		12. REPORT DATE November 1983
		13. NUMBER OF PAGES
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report) Approved for public release, distribution unlimited.		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number)		
Combustion	Temperature	Spectroscopy
Flame	Infrared	Turbulent
Diagnostics	Absorption	Fluorescence
Laser	Raman	Reacting
		Fiberoptic
		Probe
		Evaporation
		Flow
		Visible
		Ultraviolet
		Visualization
		Fast-Scanning
20. ABSTRACT (Continue on reverse side if necessary and identify by block number)		
<p>Progress is reported for the third year of an interdisciplinary program to innovate modern diagnostic techniques for application to reacting flows. Project areas are: (1) fiber optic absorption/fluorescence probes for species measurements employing tunable ultraviolet, visible and infrared laser sources; (2) wavelength modulation spectroscopy, using rapid-scanning ultraviolet, visible and infrared laser sources, for measurements of species, temperature and absorption lineshapes, (3) quantitative flow visualization, including</p>		

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE(When Data Entered)

Block No. 20 (Abstract) continued

/ temporally and spatially resolved species measurements in a plane, using laser-induced fluorescence; (4) multiple-point velocity visualization; (5) plasma diagnostics, utilizing planar laser-induced fluorescence and wavelength modulation techniques; (6) diagnostic techniques for thermionic converter plasmas; (7) application of advanced diagnostic techniques for studies of turbulent reacting flows; (8) development of measurement techniques and a novel facility for investigations of droplet evaporation in turbulent flows; (9) holographic display techniques for 3-D visualization of flowfield data; (10) coherent anti-Stokes Raman spectroscopy (CARS) for temperature and velocity measurements in a supersonic jet; and (11) computed absorption tomography system for species measurements in a plane.

Accession For	
NTIS GRA&I	<input checked="checked" type="checkbox"/>
DTIC TAB	<input type="checkbox"/>
Unannounced	<input type="checkbox"/>
Justification	
By _____	
Distribution/	
Availability Codes	
Dist	Avail and/or Special
A-1	



UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE(When Data Entered)

TABLE OF CONTENTS

<u>Section</u>	<u>Page</u>
1.0 INTRODUCTION	1
2.0 PROJECT SUMMARIES.....	3
2.1 Fiber Optic Absorption/Fluorescence Probes.....	3
2.2 Wavelength Modulation Spectroscopy.....	9
2.3 Quantitative Flow Visualization.....	18
2.4 Velocity Visualization.....	26
2.5 Plasma Diagnostics (Quantitative Visualization).....	34
2.6 Diagnostic Techniques for Thermionic Converter Plasmas..	38
2.7 Application of Diagnostic Techniques to Turbulent Reacting Flows.....	40
2.8 Concentration Measurements in Evaporating Flows.....	46
2.9 Three-Dimensional Flow Visualization (Holography).....	55
2.10 Coherent Anti-Stokes Raman Spectroscopy (CARS).....	67
2.11 Computed Absorption Tomography.....	72

AIR FORCE OFFICE OF SCIENTIFIC RESEARCH (AFSC)
 NOTICE OF REPLY TO DTIC
 This technical report has been reviewed and is
 approved for release under E.O. 13526-12.
 Distribution is unlimited.
 MATTHEW J. KERRER
 Chief, Technical Information Division

1.0 INTRODUCTION

Progress is reported for the third year of an interdisciplinary program to innovate advanced diagnostic techniques for application to reacting flows. Project areas are: (1) fiber optic absorption/fluorescence probes, employing tunable ultraviolet, visible and infrared laser sources for remote species measurements; (2) wavelength modulation spectroscopy, using rapid-scanning ultraviolet, visible and infrared laser sources for measurements of species, temperature and absorption lineshapes; (3) quantitative flow visualization, using laser-induced fluorescence for temporally and spatially resolved species measurements in a plane; (4) multiple-point velocity visualization; (5) plasma diagnostics, with emphasis on planar laser-induced fluorescence and wavelength modulation techniques; (6) diagnostic techniques for thermionic converter plasmas; (7) application of advanced diagnostic techniques for studies of turbulent reacting flows; (8) development of measurement techniques and a novel facility for investigations of droplet evaporation in turbulent flows; (9) holographic display techniques for 3-D visualization of flowfield data; (10) coherent anti-Stokes Raman spectroscopy (CARS) for temperature and velocity measurements in a supersonic jet; and (11) computed absorption tomography system for species measurements in a plane.

2.0 PROJECT SUMMARIES

Included in this section are summaries of progress in each of eleven project areas. Each project summary contains the following sub-sections: (a) Introduction; (b) Scientific Merit; (c) Status Report; (d) Publications and Presentations; (e) Personnel. Additional descriptions of this work may be found in the cited publications and in our previous scientific reports (November 1981 and November 1982).

2.1 Fiber Optic Absorption/Fluorescence Probes

Introduction

Optical fibers provide a convenient and flexible means of linking expensive and environmentally sensitive laser sources with remote and possibly hostile test facilities. Additionally, fiber links facilitate multiplexed laser measurements, that is the use of one laser to make measurements at a number of locations. With regard to combustion needs, optical fibers offer perhaps the best prospect for extending some of the laser-based diagnostic techniques developed in small-scale laboratory combustors to larger-scale systems, particularly those with limited optical access.

With optical fiber technology, it becomes possible to consider measurements of a wide variety of physical quantities using various sensing schemes. In our work, we have been primarily interested in gaseous species and temperature measurements, and we have focused our efforts on the use of laser absorption and fluorescence which offer advantages with regard to sensitivity and simplicity of operation and interpretation. In the past few years we have reported on a series of approaches and devices (see publications listed at end of this section) for combustion measurements, using various laser sources (tunable IR diode lasers and both cw and pulsed tunable UV/visible dye lasers). As our past work in this area is well documented, we report here only our most recent activity involving the use of an optic fiber link to enable absorption-based measurements of NCO in a shock tube located in a separate building 60 meters from the dye laser source.

Scientific Merit

This research seeks to provide practical spectroscopy-based schemes for measurements of gaseous concentrations in combustion flows. Such schemes are critically needed for flows with poor optical access or where the test environment precludes local placement of a laser source. Our approach is unique in that it seeks to combine recently developed tunable laser sources with novel absorption or fluorescence probes. The resulting, relatively simple diagnostics are well suited to meet a variety of practical measurement requirements and hence have the potential for significant impact on various scientific and engineering aspects of combustion and propulsion.

Status Report

We limit our discussion here to recent, unpublished work. The reader is referred to the publications list at the end of this section for a full description of past work.

Our major activity during this reporting period has been in the development of a fiber optic absorption technique for monitoring NCO in a shock tube. The species NCO has been proposed, on theoretical grounds, as a combustion intermediate of some importance in connection with the chemistry of nitrogen species in combustion. Until now, however, NCO has not been detected in a high temperature system. In our work (partially supported by the EPA) we have: investigated the electronic absorption spectra of NCO ($B \leftarrow X$ and $A \leftarrow X$ bands), found an optimum wavelength for detection, modified our Ar^+ -pumped cw ring dye laser to operate at this near-UV wavelength (440 nm, $A \leftarrow X$ band), installed a 60 meter optical fiber link between the laser and the shock tube lab, and performed incident shock wave tests to evaluate the detection limits of the system. The portions of the work supported by this AFOSR program are reported here.

A schematic of the experiment and typical results are shown in Fig. 1. The laser source was a ring dye laser (Spectra-Physics 380A) operating on stilbene (S3) dye and pumped by the UV lines (1.9 W, all

lines) of an Ar^+ laser (Spectra-Physics 171-18). The output of the laser was amplitude stabilized (Coherent 307 Noise Eater), yielding power levels of 5-10 mW at the input of the 60 meter fiber link (200 micron fused silica fiber, Superguide).

The quantity measured was the fractional absorption, which could be converted via Beer's law to a mole fraction for NCO. After optimization, the detection limit of the system was about 0.2 percent absorption, corresponding to 1 ppm of NCO at typical conditions. A representative record of NCO absorption, obtained in a shock-heated $\text{O}_2/\text{N}_2\text{O}/\text{C}_2\text{N}_2$ mixture at 0.6 atm, 1440 K is shown in Fig. 1. A sharp Schlieren spike indicates passage of the shock, temporarily deflecting a portion of the beam from the detector and giving an apparent absorption signal. Following a short induction time the absorption signal increases to a plateau level corresponding to 22 ppm of NCO. This record can be compared with kinetic calculations to infer rate constants for the two reactions: $\text{O} + \text{NCO} \rightarrow \text{CO} + \text{NO}$ and $\text{NCO} + \text{M} \rightarrow \text{N} + \text{CO} + \text{M}$.

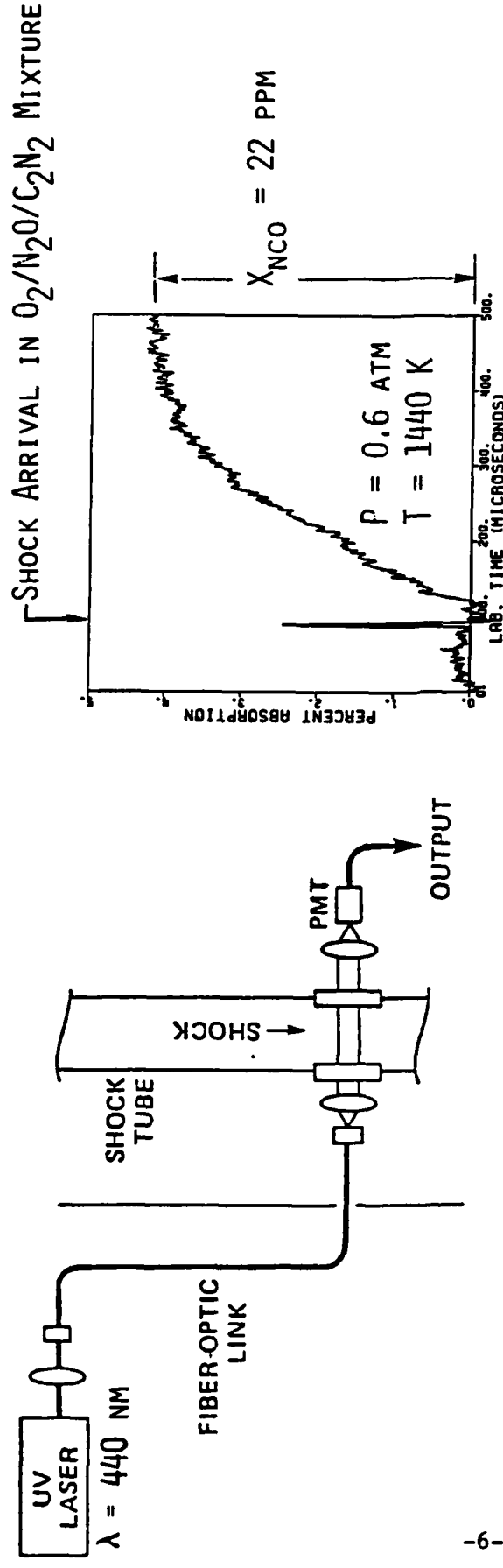
The significance of this work is twofold: (1) we have established a method for quantitatively monitoring NCO and have made the first measurements of NCO in a high temperature system; and (2) we have demonstrated the utility of fiber optic links for sensitive, quantitative species measurements at locations removed from the laser source. The latter accomplishment suggests the potential of using expensive and sensitive laser sources for measurements at several locations, thereby increasing the utility factor of such systems and enabling sharing of facilities between different experiments and research groups.

Publications and Presentations

Presentations

1. G. Kychakoff and R.K. Hanson, "Optical Fiber Probe Using Tunable Laser Absorption Spectroscopy for Combustion Measurements," presented at 1981 Los Alamos Conference on Optics, April 1981.
2. S.M. Schoenung and R.K. Hanson, "Laser Absorption Sampling Probe for Spatially and Temporally Resolved Combustion Measurements," presented at 1981 Conference on Lasers and Electro-Optics (CLEO), Washington, June 1981.

SUCCESSFUL USE OF FIBER-OPTIC LINK TO REMOTELY MEASURE CONCENTRATIONS IN HOSTILE ENVIRONMENT



Fiber-Optic Link to Shock Tube Experiment

Rate of NCO Increase used to Establish Kinetic Relationship

- FIBER OPTIC LINK ENABLES USE OF LASER SOURCES FOR REMOTE MEASUREMENTS IN HOSTILE SYSTEMS
- MULTIPLE MEASUREMENT LOCATIONS WITH SINGLE LASER DEMONSTRATED
- FIRST OBSERVATION OF NCO AT HIGH TEMPERATURES
- TECHNIQUE ENABLES DETERMINATION OF SPECTRAL PARAMETERS AT HIGH TEMPERATURES

Figure 1. Schematic of system used to monitor NCO in a shock tube using a remotely located dye laser.

3. S.M. Schoenung and R.K. Hanson, "Temporally and Spatially Resolved Measurements of Fuel Mole Fraction in Turbulent CO Diffusion Flame," paper WSS/CI 81-33 at Western States Section, Combustion Institute meeting, Phoenix, October 1981.
4. G. Kychakoff and R.K. Hanson, "Tunable Laser Absorption/Fluorescence Fiberoptic Probe for Combustion Measurements," paper WSS/CI 81-50 at Western States Section, Combustion Institute meeting, Phoenix, October 1981.
5. G. Kychakoff, R.D. Howe and R.K. Hanson, "Spatially Resolved Combustion Measurements Using Crossed-Beam Saturated Absorption Spectroscopy," paper THM2 at CLEO '82, Phoenix, Az., April 14-16, 1982.
6. M.A. Kimball-Linne, G. Kychakoff, R.K. Hanson and R.A. Booman, "A Fiber Optic Fluorescence Probe for Species Measurements in Combustors," paper 82-50 at Western States Section, Combustion Institute meeting, Livermore, Ca., October 11-12, 1982.

Publications

1. S.M. Schoenung and R.K. Hanson, "CO and Temperature Measurements in a Flat Flame by Laser Absorption Spectroscopy and Probe Techniques," Combustion Science and Technology 24, 227-237 (1981).
2. S.M. Schoenung and R.K. Hanson, "laser Absorption Sampling Probe for Spatially and Temporally Resolved Combustion Measurements," Applied Optics 21, 1767-1771 (1982).
3. S.M. Schoenung and R.K. Hanson, "Temporally and Spatially Resolved Measurements of Fuel Mole Fraction in a Turbulent CO Diffusion Flame," 19th Symposium (International) on Combustion, The Combustion Institute, pp. 449-458 (1982).
4. G. Kychakoff and R.K. Hanson, "Optical FiberProbe Using Tunable Laser Absorption Spectroscopy for Combustion Measurements," The Los Alamos Conference on Optics, 81, D.L. Liebenbert, Ed., Proc. SPIE 288, 236 (1982).
5. R.K. Hanson, S. Salimian, G. Kychakoff and R.A. Booman, "Shock Tube Absorption Measurements of OH Using a Remotely Located Dye Laser," Applied Optics, 21, 641 (1983).
6. G. Kychakoff, M.A. Kimball-Linne and R.K. Hanson, "Fiber-Optic Absorption/Fluorescence Probes for Combustion Measurements," Applied Optics 22, 1426 (1983).
7. M.Y. Louge and R.K. Hanson, "Shock Tube Study of NCO Spectroscopy Using a Remotely Located Dye Laser," to be published.

Personnel

Ronald K. Hanson	Professor (Research), Mechanical Engineering
George Kychakoff	Graduate Student, Mechanical Engineering (Ph.D. expected in December 1983)
Susan Schoenung	Graduate Student, Mechanical Engineering (Ph.D. awarded in June 1982)
Mark A. Kimball-Linne	Graduate Student, Mechanical Engineering (Ph.D. expected in June 1984)
Richard A. Booman	Research Engineer, Mechanical Engineering
Michel Y. Louge	Graduate Student, Mechanical Engineering (Ph.D. expected in June 1984)

2.2 Wavelength Modulation Spectroscopy

Introduction

Recent improvements in tuning rates of narrow-linewidth laser sources offer significant potential for advancements in diagnostic techniques and combustion-related measurements using wavelength modulation spectroscopy concepts. Wavelength modulation spectroscopy refers to laser absorption or laser-induced fluorescence measurements carried out with a rapid-tuning single mode laser. In essence this method involves quickly scanning a tunable cw laser across one or more isolated absorption transitions and recording the fully resolved (spectrally) absorption line profile using either absorption or fluorescence detection. The method is generally applicable to both infrared transitions and to UV/visible transitions, when laser sources are available.

The primary advantage of wavelength modulation is that it provides a simple means of discriminating against continuum extinction effects which can seriously hinder conventional laser absorption or fluorescence measurements in two-phase flows. Moreover, recording the fully resolved absorption line eliminates the need for uncertain linewidth assumptions in converting measured absorption (or fluorescence) to species concentration or temperature. Previously in our laboratory, in an AFOSR-sponsored program, we demonstrated the utility of the wavelength modulation concept for measurements involving infrared-active species using a commercially available rapid-tuning infrared diode laser.

Unfortunately, rapid-tuning dye lasers, needed for accessing a variety of important radical species which absorb in the near UV and visible, are not commercially available. Recognizing the importance of such a capability, we have in the past year developed a novel (and simple) modification to a commercial ring dye laser which increases the scan repetition rate by three orders of magnitude (from about 4 Hz to 4 kHz) for short scans (up to $5 \text{ cm}^{-1} = 150 \text{ GHz}$), and we have recently incorporated intracavity frequency doubling into the dye laser to permit access to UV wavelengths. Operation in the UV is critical for access to a variety of important combustion radical species.

Scientific Merit

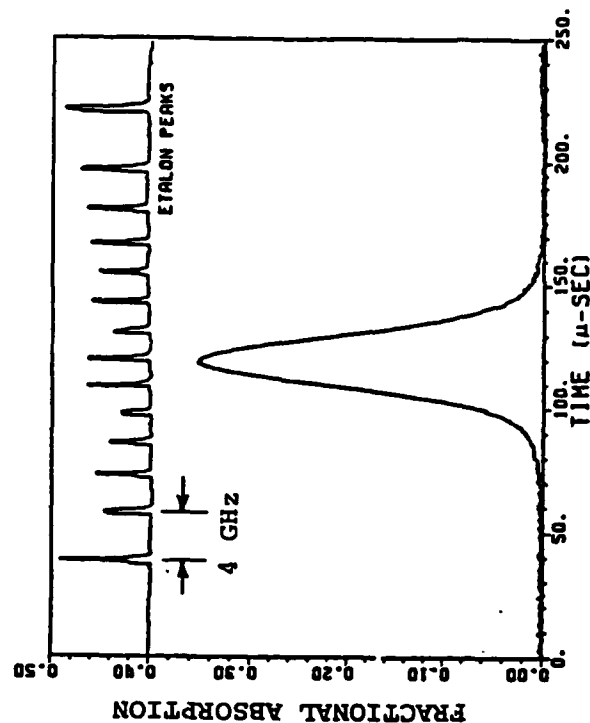
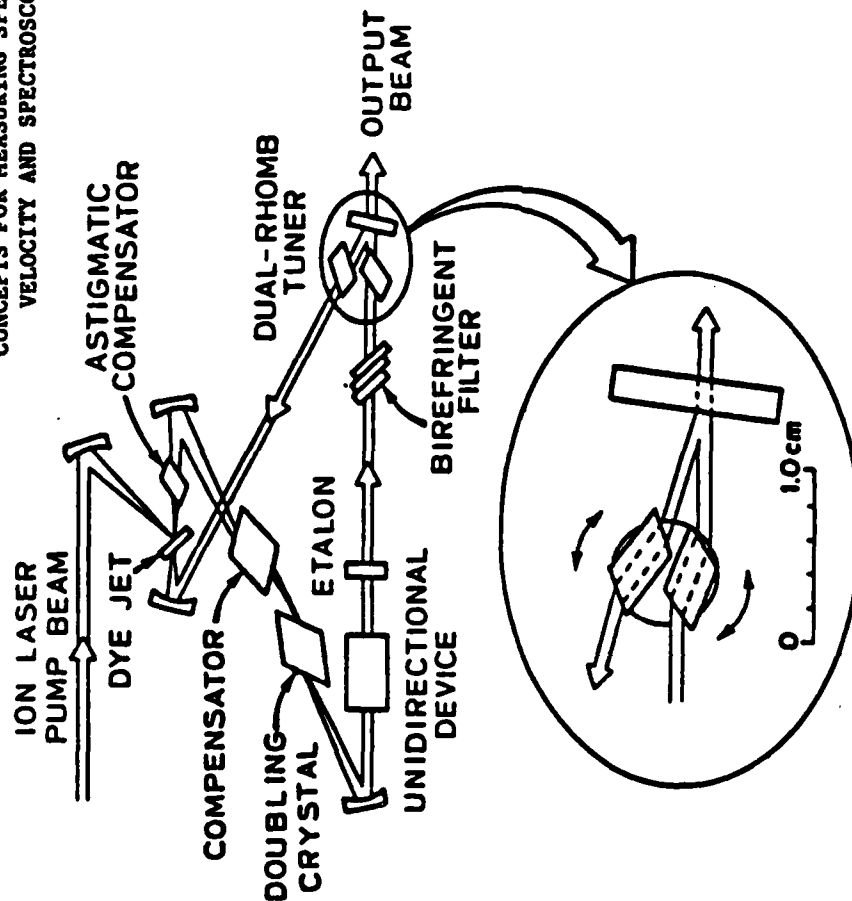
This is the first dye laser system we are aware of which enables fast single-mode scans over spectral regions encompassing complete absorption lines (~ 30 GHz at combustion conditions). This capability provides several new opportunities for combustion research. In connection with practical combustors or laboratory devices where particulates or droplets are present, wavelength-modulation techniques can now be applied to discriminate between the gaseous absorption of interest and the interfering continuum extinction. In unsteady flows or in devices where transient phenomena are of interest, fast measurements of fully-resolved absorption or fluorescence lines can be used for time-resolved determinations of species and temperature. Finally, the significance of fast-scanning capability for basic spectroscopic measurements should be noted. For example, it is now possible to record fully resolved absorption lines in a shock tube. Such experiments can yield unique data on linewidths at elevated temperatures, and offer prospects of determining fundamental quantities such as oscillator strengths and heats of formation of radical species important in various combustion flows.

Status Report

A schematic of the dye laser modification and an example of the system capability to monitor an isolated uv absorption line of OH in a flame are shown in Fig. 1. In brief, a rotating dual-element device, which changes the effective laser pathlength as it rotates, is installed in one corner of the ring laser adjacent to the output mirror. Use of two elements guarantees that the alignment of the beam (inside and outside of the cavity) does not change while the wavelength is changing. The tuning elements are mounted on the shaft of a commercial galvanometer which mounts conveniently in the standard ring cavity of our Spectra-Physics ring dye laser.

The tuner was demonstrated initially at visible wavelengths, providing continuous, single-mode scans of up to 5 cm^{-1} (150 GHz) at 4 kHz. Recently we have been able to extend this capability into the UV by installing a doubling crystal into the same cavity. Experiments with an

RAPID SCANNING RING DYE LASER ENABLES NEW WAVELENGTH-MODULATION
CONCEPTS FOR MEASURING SPECIES, TEMPERATURE,
VELOCITY AND SPECTROSCOPIC PARAMETERS



SINGLE SWEEP RECORD OF FULLY RESOLVED OH
ABSORPTION LINE OBTAINED BY PASSING TUNABLE
LASER BEAM THROUGH FLAME.

- MODIFICATION IMPROVES SCANNING RATE OF LASER FROM $4 \text{ Hz} \rightarrow 4 \text{ kHz}$ (60 GHz SCAN)
- SYSTEM PROVIDES FIRST HIGH-SPEED, HIGH SPECTRAL RESOLUTION CAPABILITY FOR STUDIES OF TRANSIENT PHENOMENA
- WAVELENGTH MODULATION CONCEPT ENABLES QUANTITATIVE ABSORPTION AND FLUORESCENCE MEASUREMENTS IN 2-PHASE FLOWS
- APPLICATIONS INCLUDE STUDIES IN FLAMES, SHOCK TUBES, SUPERSONIC FLOWS, COMBUSTION TUNNELS
- SYSTEM ENABLES UNIQUE MEASUREMENT OF BASIC PARAMETERS IN HIGH TEMPERATURE CASES (F-NUMBERS, LINESHAPES, ΔH_f)
- CONCEPT APPLICABLE FOR UV, VISIBLE AND NEAR IR WAVELENGTHS

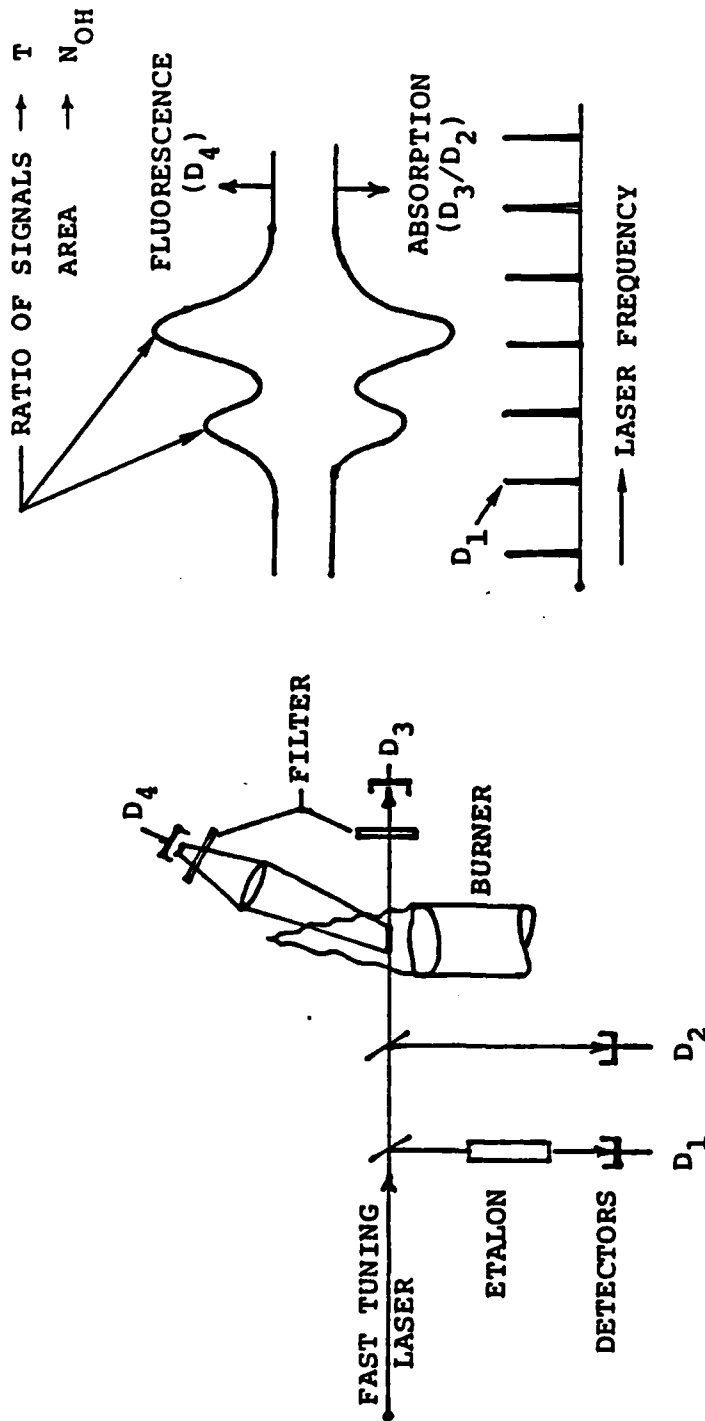
Fig. 1 Schematic of fast-scanning ring dye laser and typical data obtained in a flame.

AD*A doubling crystal, oven and mount provided by Spectra-Physics (recently released as model 398A) show excellent performance (see Fig. 1), with output in excess of 5 mW at 309 nm (with a pump power of only 4 W all lines) and single mode scans of more than 100 GHz at 4 kHz repetition rate. We have been contacted by several researchers in other laboratories who are anxious to obtain this extended capability.

We have utilized this new tuner in two novel experiments, one conducted with a shock tube and one in a flame. In the shock tube experiment, the laser was used to record fully resolved absorption line profiles of OH over a range of post-shock conditions. In brief, the center frequency of the repetitively scanning laser was set on a known UV line of OH, and the beam was passed through the shock tube to enable recording of absorption line profiles behind incident shock waves. Mixtures of $H_2/O_2/Ar$ were shock heated to provide relatively constant levels of OH at known conditions. These experiments, now being written up for publication, provide the first fully resolved, radical species absorption spectra recorded in a shock tube. Use of the fast-scanning laser in conjunction with shock tube methods provides several new opportunities for fundamental research on spectral and thermochemical properties of high temperature gases.

The second novel experiment which we have conducted with the new rapid-tuning dye laser involves combined absorption and fluorescence measurements in a flame. A simplified schematic diagram of the experiment indicating the essential features of the set-up and an illustration of the type of data recorded are shown in Fig. 2. A more detailed diagram of the set-up is given in Fig. 3. In this work we have chosen to scan a portion of the OH absorption spectrum encompassing two transitions. This is an important aspect of our measurement strategy, because it should enable inference of both temperature (from the relative strengths of the two lines) and species concentration (from absolute measurements of the area of one of the lines). The capability for simultaneous temperature and species concentration measurements demonstrated here using one laser source are quite exciting, particularly since the method appears capable of monitoring these quantities at high repetition

WAVELENGTH MODULATION SPECTROSCOPY
 ENABLES SIMULTANEOUS TEMPERATURE, SPECIES MEASUREMENTS



- First Simultaneous T, NOH Measurements in a Flame
- Significant Advance in Measurement Repetition Rate (10 Hz to 4 kHz)
- Experiments Yield Fundamental Spectroscopy Parameters Directly
- Data Reduction Avoids Usual Assumptions of Lineshape
- Absorption Enables Calibration of Fluorescence

Fig. 2 Schematic of wavelength modulation spectroscopy experiment in a flame.

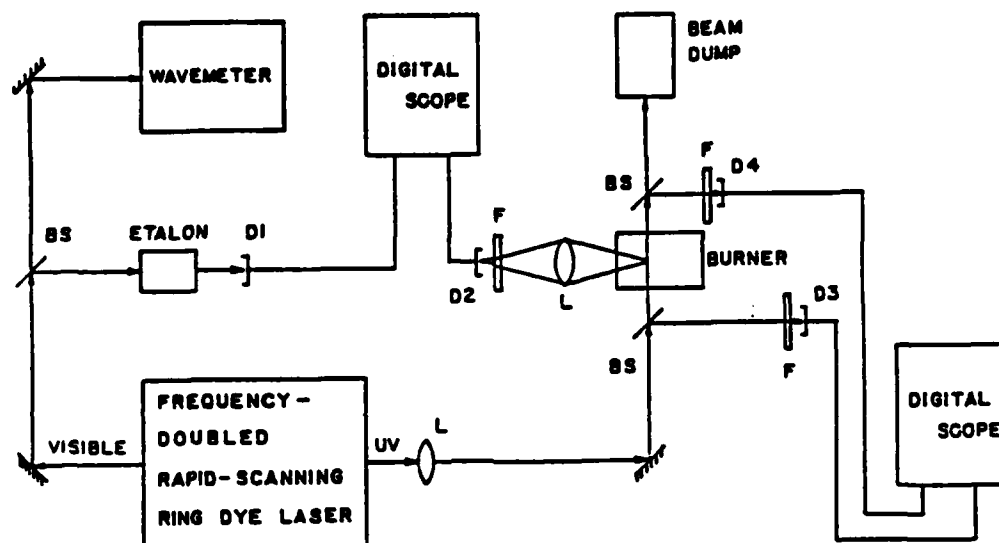


Fig. 3 Schematic diagram of absorption/fluorescence experiments.

BS - fused silica beamsplitters; L - quartz lenses;
 F - Corning 7-54 glass filters; D1 - etalon monitor detector;
 D2 - fluorescence detector (RCA 1P28)
 D3,D4 - transmission detectors (EG&G UV100b)

rates. At present, CARS measurements, which can yield temperature but not minor species, are capable of only about 10 Hz repetition rate. The successful development of a method yielding both temperature and species concentration at kilohertz repetition rates would therefore represent a major diagnostics advance. Although challenges remain, this is our goal and good progress is being made.

An example of typical absorption data obtained in a near-stoichiometric CH_4 -air flat flame are shown in Fig. 4. The quantity plotted is the logarithm of the fractional transmission, normalized by the peak value, for a single-sweep (about 200 microsecond duration) scan of the laser. The data are fit using a best-fit Voigt profile analysis in which temperature is the principal unknown. The inferred temperature, 1925 K, is in excellent agreement with radiation-corrected thermocouple readings. The accuracy of the absorption-based temperature is extremely good; we estimate an uncertainty of under 1.5%. It must be remembered, of course, that this is a line-of-sight measurement, and while such

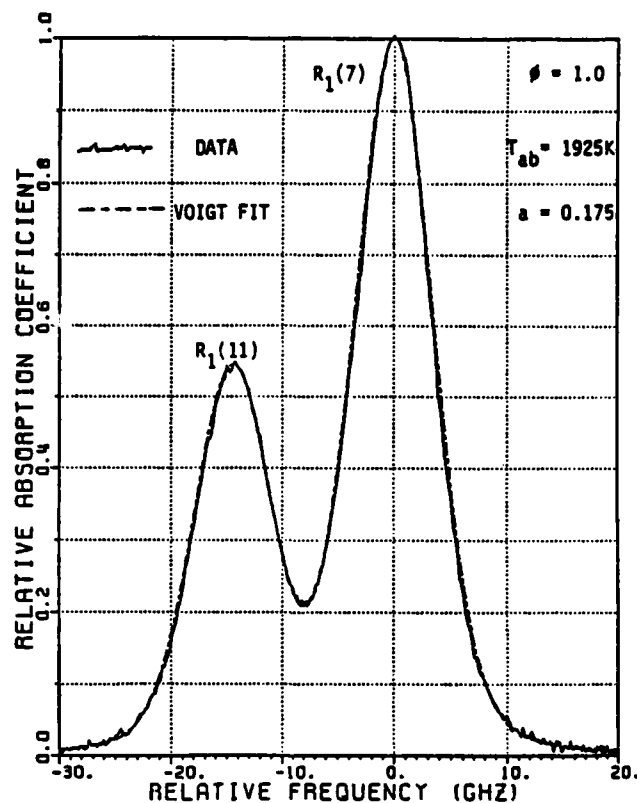


Fig. 4 Single sweep absorption trace and Voigt fit for wavelength modulation experiment in a flat flame burner; $\phi = 1.0$.

measurements will be useful for many purposes they do not yield the spatial resolution needed for fundamental studies of turbulence. As of this writing, we have not yet extracted values of OH concentration from these records, although we anticipate no problems in doing so.

Similar, single-sweep fluorescence data (for a somewhat leaner flame) are shown in Fig. 5, again plotted together with a best-fit theoretical profile enabling determination of temperature. These data are noisier, owing to the much smaller signal with fluorescence, but the results are still very encouraging in that the fluorescence temperature agrees within a few percent with the thermocouple value.

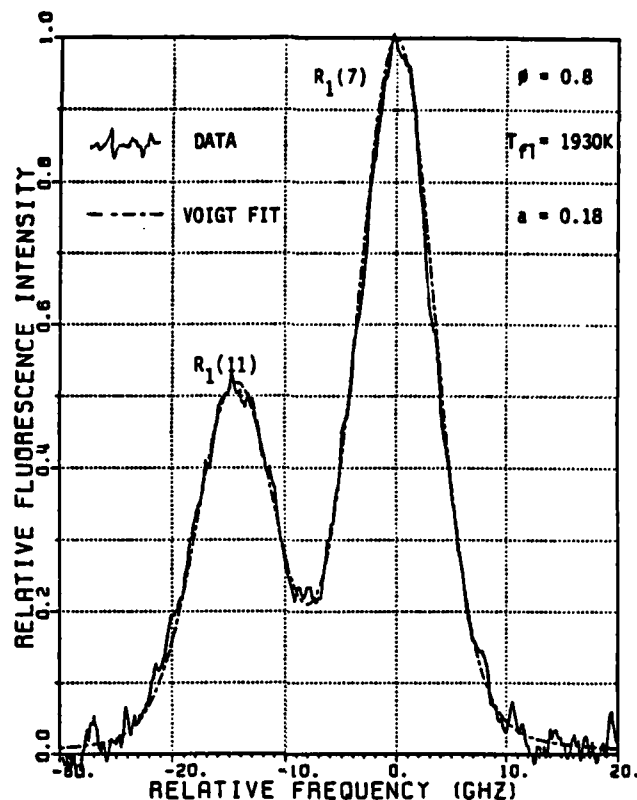


Fig. 5 Single sweep fluorescence trace and Voigt fit for wavelength modulation experiment in a flat flame burner; $\phi = 0.8$.

Publications and Presentations

1. E.C. Rea, Jr., and R.K. Hanson, "Rapid Extended Range Tuning of Single-Mode Ring Dye Lasers," *Applied Optics* **22**, 518 (1983).
2. E.C. Rea, Jr. and R.K. Hanson, "Fast-Scanning UV Ring Dye Laser for Combustion Research," presented at CLEO '83, Baltimore (May 1983).
3. R.K. Hanson, S. Salimian and E.C. Rea, Jr., "Laser Absorption Techniques for Spectroscopy and Chemical Kinetics Studies in a Shock Tube," presented at 14th International Shock Tube Symposium, Sydney, August 1983; to be published in *Shock Tubes and Waves*, 1984.
4. R.K. Hanson, "Tunable Diode Laser Measurements in Combustion Gases," paper 438-12 presented at 1983 meeting of Soc. Photographic and Inst. Engineers, San Diego, August 1983; to be published in bound proceedings.

5. E.C. Rea, Jr. and R.K. Hanson, "Fully Resolved Absorption/Fluorescence Lineshape Measurements of OH Using a Rapid-Scanning Ring Dye Laser," paper 83-66 at the fall meeting of the Western States Section/Combustion Institute, Los Angeles, CA, October 1983.

Personnel

Ronald K. Hanson

Professor, Mechanical Engineering

E.C. Rea, Jr.

Graduate Student, Mechanical Engineering
(Ph.D. Expected in June 1985)

2.3 Quantitative Flow Visualization

Introduction

The utility of flow visualization as a diagnostic in studies of fluid mechanics and combustion is well established. Until recently, however, most visualization techniques have been qualitative and based on line-of-sight approaches poorly suited for flows with three-dimensional characteristics. With the recent development of laser-based light scattering techniques, it has become possible to obtain spatially and temporally resolved quantitative records of flow properties throughout a plane (and ultimately throughout a volume) using sheet illumination and a scattering technique such as Raman, fluorescence or Mie scattering. Work along these lines is now in progress at Stanford, Yale, SRI and Sandia (Livermore). As an example of the capability of these new methods, in our laboratory at Stanford we are now able to make instantaneous (8 nsec), multiple-point (10^4 flowfield points) measurements of species (OH, NO and Na) in a variety of laboratory flames using planar laser-induced fluorescence (PLIF). The sensitivity demonstrated thus far is in the 10's of ppm range, with spatial resolution typically much better than 1 mm. Of equal importance, we have recently demonstrated variations of this approach which yield temperature and velocity (see Section 2.4) at multiple points without particle seeding. These new techniques provide significant advances in measurement capability with important applications which extend well beyond the field of combustion for which they were originally developed.

Scientific Merit

This is a fast-moving area of research with the potential to stimulate scientific advances in several fields, including but not limited to fluid mechanics and combustion. Development of these visualization techniques may also contribute to related technologies, such as lasers and image processing, and provide fundamental data for fields such as spectroscopy. In a sense, the thrust of the work is, as is now the case in many areas of science, "information processing". Our goal is to establish means of acquiring and processing orders-of-magnitude more

information (data) on flows than can be obtained with single-point measurements. In order to develop advanced diagnostic systems with such potential, we must meet a number of interdisciplinary challenges ranging from optimization of the physical sensing process to solution of problems involving the processing, display and even the interpretation of such expanded data sets.

Status Report

A detailed schematic of our current diagnostics system, suitable for intermittent single-frame recording of PLIF images of species in a plane, is shown in Fig. 1. The pulsed dye laser is a Quanta-Ray system, tunable (with charges of dye and mixing crystals) from 220-900 nm. The detection system is an EG&G Reticon photodiode array (100 x 100) which has been intensified (ITT) with a dual-microchannel-plate intensifier. The output of the Reticon array is fed via a Microtex 7400 camera-to-computer buffered interface to a DEC 11/23 computer. The PLIF images or "frames" are subsequently displayed on a color monitor or output on a plotter.

During this past year, PLIF results have been obtained for Na (590 nm), OH (285 and 306 nm) and NO (225 nm) in several combustor flow-fields. Here we emphasize only the most important accomplishments, which include: (1) an initial demonstration of the applicability of PLIF for visualizing sooting combustion flows; (2) a demonstration of PLIF measurements for quantitative visualization of mixing phenomena in combustion flows, using NO as a tracer species; and (3) extension of the visualization recording system to enable operation at high repetition rates, up to at least 400 Hz.

The development of PLIF capability for two-phase flows is critical if PLIF is to be useful for studies of practical combustion devices and for fundamental research on droplet and solid propellant combustion. An example of single-shot PLIF measurements of OH in a small-scale, sooting diffusion flame is shown in Fig. 2. The strategy employed to discriminate against elastically scattered laser light was to utilize separate electronic transitions for excitation and detection, namely excitation

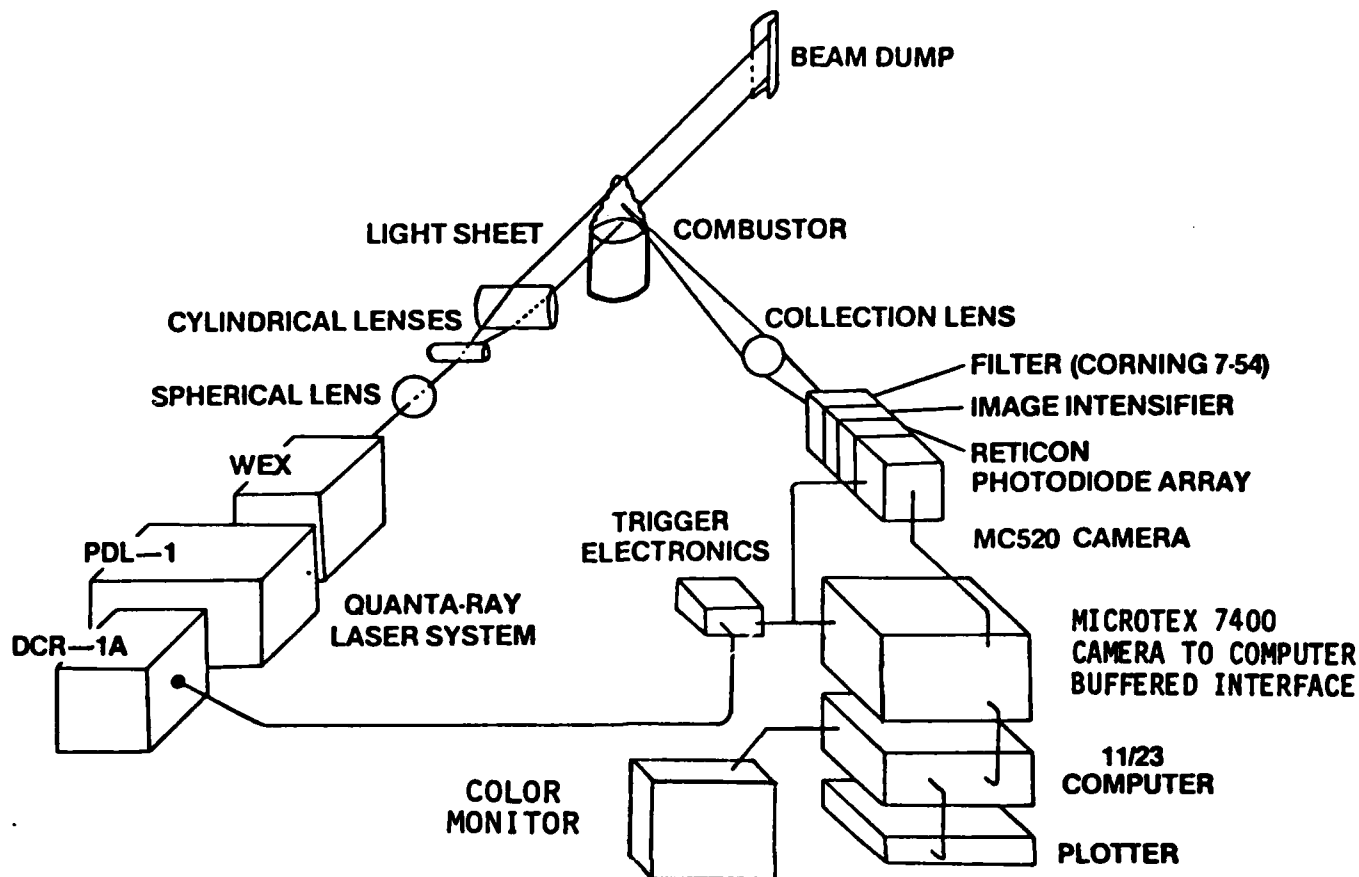


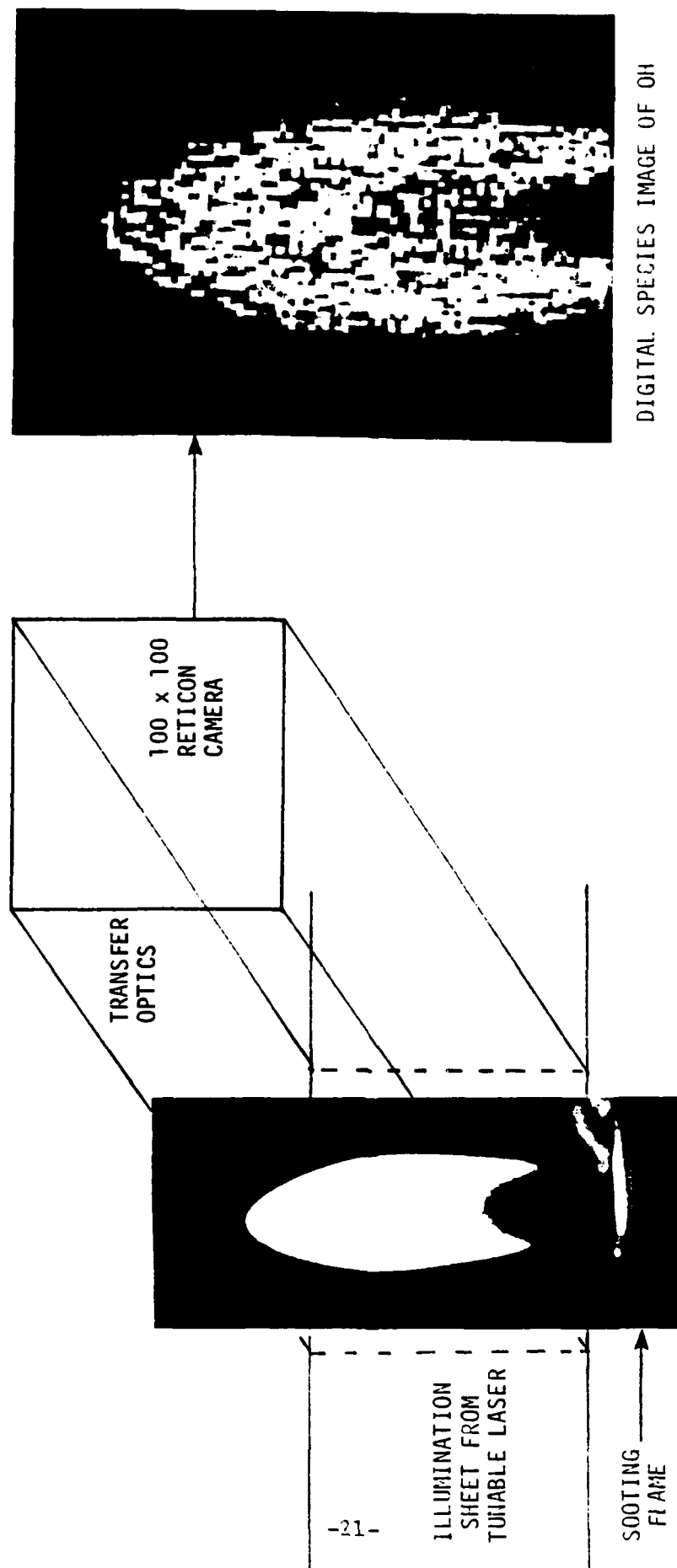
Fig. 1 Detailed schematic of first-generation electro-optic system for PLIF species measurements in flames.

via the (1,0) band of OH ($A^2\Sigma + X^2\Pi$ system) near 285 nm and detection of the (1,1) band near 315 nm. As can be seen in Fig. 2, the results are free from effects of particulate scattering. Current research is concerned with extending this capability to spray combustion.

Owing to the importance of mixing phenomena in combustion research, we have worked to establish a variation of PLIF which enables quantitative visualization of mixing. This capability is demonstrated in Fig. 3 for mixing between combustion gases produced in a flat flame burner and ambient air. The premixed combustion gases are seeded with about 2000 ppm of an inert tracer species, in the present case NO, enabling visualization of the mixing by monitoring laser-induced fluorescence of NO. The PLIF signal is proportional to the local mole fraction of NO and

QUANTITATIVE FLOW VISUALIZATION

PLANAR LASER-INDUCED FLUORESCENCE (PLIF) YIELDS
2-D CONCENTRATIONS IN SOOTING FLAMES



- FIRST INSTANTANEOUS MULTIPLE-POINT SPECIES MEASUREMENTS IN A SOOTING FLAME (10^4 POINTS)
- HIGH SPATIAL ($0.4 \times 0.4 \times 0.2$ MM) AND TEMPORAL (5 NSEC) RESOLUTION
- POTENTIAL MAJOR IMPACT ON COMBUSTION MODELLING

Fig. 2 Highlights of quantitative flow visualization project.

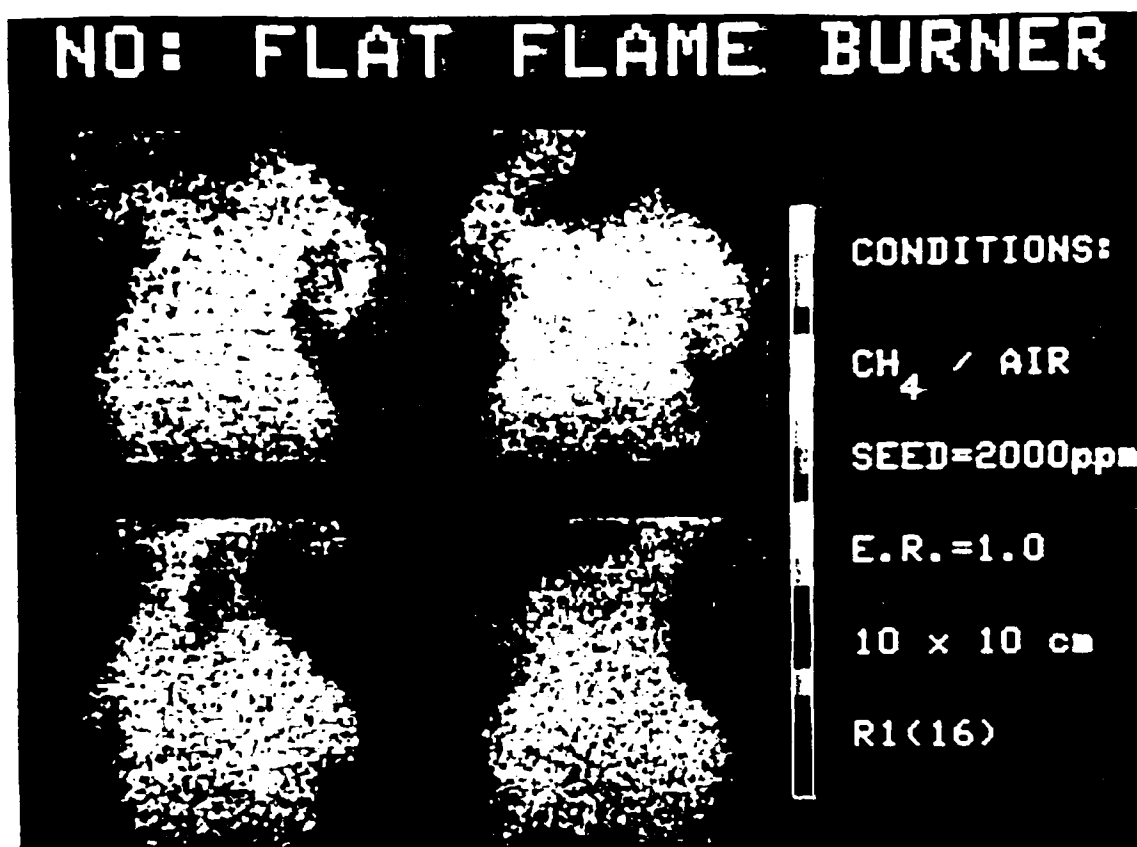


Fig. 3 Flat Flame Burner: Bottom: photograph (1 sec exposure); Top: Four separate instantaneous measurements in a vertical plane using PLIF and NO seeding to visualize mixing with surrounding air (8 nsec exposures). Note the unsteady nature and large-scale structures made apparent by the visualization technique.

hence indicates the extent of mixing of the combustion gases with the ambient air. An interesting feature of these results is the appearance of large-scale structures at the mixing boundary, as have been observed in a variety of non-combusting flowfields. Such structures are a subject of active research in the fluid mechanics community, and hence these results graphically demonstrate the utility of PLIF as a diagnostic for such research.

Another important accomplishment during the past year has been the upgrading of the recording speed of our PLIF system so that, with the exception of our current pulsed laser source (limited to 10 Hz repetition rate), we are now able to record at up to 400 frames/sec. This capability has been demonstrated (to 200 frames/sec) using a cw dye laser source to excite Na in a small-scale burner, yielding our first "high-speed movie" of species in a plane. Although the cw laser is not suitable for exciting the major and radical species of primary interest, this experiment serves to illustrate the type of information which can be obtained with this approach. We plan to purchase a 350 Hz pulsed dye laser during the next year to enable further work in this area. The capability to record (as well as process and display) multiple frames at high rates is important because it will allow monitoring the real-time evolution of fluid structures. Such data are not presently available and are of fundamental importance for the development of improved combustion and fluid mechanics models.

Finally, we should note that progress has been made in transferring PLIF technology to other users in the fields of fluid mechanics and combustion science. A number of visitors to our laboratory in the past year have been especially interested in our work on species and velocity visualization, and we have responded to several follow-up inquiries for technical information needed to specify proposed systems for these researchers. In addition, we were able to demonstrate directly the ease of transferring this technology by carrying out a short series of collaborative experiments at the GE/Research and Development Laboratories (Schenectady) in September 1982. In brief, GE provided the combustion flow facility, the tunable pulsed laser source and a host computer,

while we provided the intensified camera and software. Within a few days, the experiment was operational, and unique OH visualization data were acquired in a turbulent jet flame. A brief report of this collaborative effort has been submitted to Science, co-authored by the Stanford and GE researchers (Drs. Lapp, Drake, Penney and Pitz), and is scheduled to appear in January 1984.

Publications and Presentations

Presentations

1. G. Kychakoff, K. Knapp, R.D. Howe and R.K. Hanson, "Quantitative Flow Visualization in Combustion Gases", paper No. 82-60, presented at Fall 1982 meeting, Western States Section/The Combustion Institute, Livermore, CA. (October 1982).
2. G. Kychakoff, R.D. Howe, R. K. Hanson and K. Knapp, "Flow Visualization in Combustion Gases," paper 83-0405, presented at AIAA 21st Aerospace Sciences Meeting, Reno (January 1983).
3. G. Kychakoff, R.D. Howe and R.K. Hanson, "Use of Planar Laser-Induced Fluorescence for the Study of Combustion Flowfields," paper 83-1361, presented at 19th Joint Propulsion Conference, Seattle (June 1983).
4. G. Kychakoff, R.D. Howe and R.K. Hanson, "Use of Planar Laser-Induced Fluorescence for Combustion Measurements," presented at CLEO '83, Baltimore (May 1983).
5. G. Kychakoff, R.D. Howe and R.K. Hanson, "Quantitative Flow Visualization Technique for Measurements in Combustion Gases," presented at the Ninth International Colloquium on the Dynamics of Explosions and Reactive Flows, Poitiers, France (July 1983).
6. J.C. McDaniel and R.K. Hanson, "Quantitative Visualization of Flowfields Using Planar Laser-Induced Fluorescence," presented at 3rd International Flow Visualization Symposium, Univ. of Michigan (September 1983).
7. R.K. Hanson, G. Kychakoff, E.C. Rea, Jr., B. Hiller, R.D. Howe and M.A. Kimball-Linne, "Advanced Diagnostics for Reacting Flows," presented at 20th JANNAF Combustion Meeting, Monterey, CA., October 1983.

Publications

1. G. Kychakoff, R. D. Howe, R. K. Hanson and J. C. McDaniel, "Quantitative Visualization of Combustion Species in a Plane," Applied Optics 21, 3225 (1982).

2. G. Kychakoff, K. Knapp, R. D. Howe and R. K. Hanson, "Flow Visualization in Combustion Gases Using Nitric Oxide Fluorescence," AIAA J., in press, to appear Dec. 1983.
3. G. Kychakoff, R. D. Howe, R. K. Hanson, M. Drake, R. Pitz, M. Lapp, and M. Penney, "The Visualization of Turbulent Flame Fronts," Science, in press, to appear Jan. 1984.
4. G. Kychakoff, R.D. Howe, R.K. Hanson and K. Knapp, "Flow Visualization in Combustion Gases," AIAA Reprint 83-0405, 21st Aerospace Sciences Meeting, Reno, Jan. 10-13, 1983.
5. G. Kychakoff, R.D. Howe and R.K. Hanson, "Quantitative Flow Visualization Technique for Measurements in Combustion Gases," paper presented at 9th Int. Coll. on Explosions and Reactive Systems, Poitiers, France, July 1983; accepted for publication by Applied Optics, in press.
6. G. Kychakaoff, R.D. Howe and R.K. Hanson, "Use of Planar Laser-Induced Fluorescence for the Study of Combustion Flowfields," AIAA Reprint 83-1361, 19th Propulsion Conference, Seattle, June 27-29, 1983; accepted for publication by AIAA J., in press.
7. R.K. Hanson, G. Kychakoff, E.C. Rea, Jr., B. Hiller, R.D. Howe and M.A. Kimball-Linne, "Advanced Diagnostics for Reacting Flows," to be published in Proceedings of 20th JANNAF Combustion Meeting, Monterey, CA., October 1983.
8. J.C. McDaniel and R.K. Hanson, "Quantitative Visualization of Flowfields Using Laser-Induced Fluorescence," to be published in Proceedings of 3rd International Flow Visualization Symposium, Univ. of Michigan, September 1983.

Personnel

Ronald K. Hanson	Professor, Mechanical Engineering
George Kychakoff	Graduate Student, Mechanical Engineering (Ph.D. Expected in December 1983)
Mark Allen	Graduate Student, Mechanical Engineering (Ph.D. expected in June 1986)
Robert Howe	Graduate Student, Mechanical Engineering
Richard Booman	Research Physicist, Mechanical Engineering

2.4 Velocity Visualization

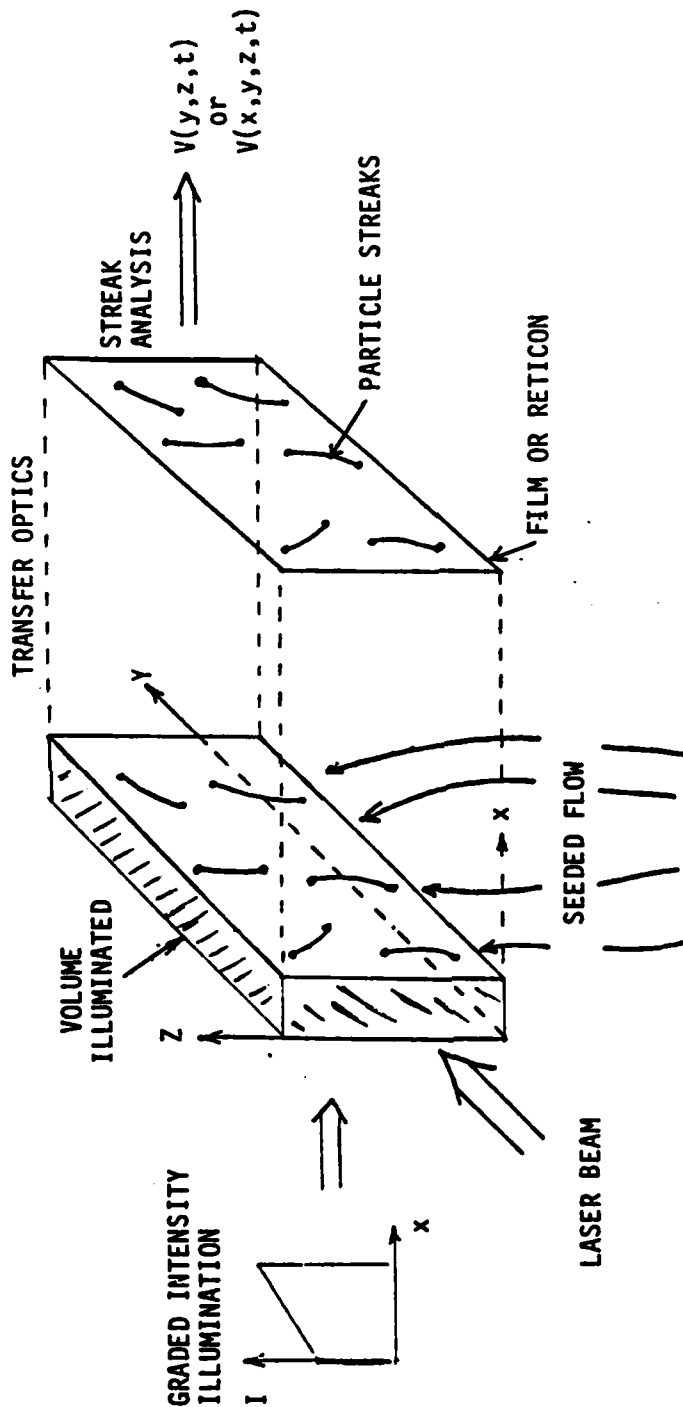
Introduction

Velocity measurements provide essential input for many fundamental and applied fluid mechanics studies. At present, hot wire anemometry and laser Doppler anemometry are the most commonly used techniques. Both methods have advantages and disadvantages, but in particular they are single-point diagnostics. Clearly, a technique yielding simultaneous multiple-point velocity data would represent a significant diagnostics contribution and could stimulate important advances in many areas involving fluid flow.

Our effort in this area was prompted in part by our success in visualizing species at multiple points in a flow (see Section 2.3) and the growing recognition that combinations of flowfield quantities (e.g., species, temperature and velocity) may eventually be needed to test advanced flow models. Accordingly, during the past year we initiated a new effort to "visualize velocity", i.e. to measure velocity at a large number of spatially resolved flowfield points leading to a computer display of velocity.

Several schemes are under consideration, two of which are indicated schematically in Figs. 1 and 2. The first method (see Fig. 1) is essentially an improved variation of streak photography and involves recording (on a Reticon array or film) streaks from particles seeded into the flow. Rather than sheet illumination, however, we envision using volume illumination with an intentional (and known) intensity gradient in the transverse direction. If the particles are spherical (so the scattering signal is independent of particle rotation) and the streaks are recorded with a photodiode array (with a response linearly proportional to intensity), then the transverse velocity can be determined from the change in signal level along the streak. The in-plane velocity is obtained directly from the streak length and the known exposure time. Problems of verifying that the particle continuously resides in the illumination region can be handled by modulating the illumination (laser) intensity or the Reticon responsivity (e.g., via the intensifier control voltage) at the beginning and end of the exposure. Although the Reticon has important advantages as a recording element (linear to intensity level, and directly interfaced

3-D VELOCITY VISUALIZATION
SIMULTANEOUS MULTIPLE-POINT MEASUREMENTS OF 3-D VELOCITY
VECTORS MADE POSSIBLE WITH QUANTITATIVE STREAK RECORDING



- FLOW IS SEEDED WITH SPHERICAL PARTICLES
- FLOW IS ILLUMINATED BY BEAM WITH INTENSITY GRADIENT
- SCATTERED LIGHT IS RECORDED ON A 2-D DETECTOR ARRAY
- VARYING INTENSITY OF PARTICLE TRACK GIVES TRANSVERSE VELOCITY (V_x)
- LENGTH OF TRACK GIVES VELOCITY IN PLANE (V_y, V_z)
- SUITABLE FOR WIDE RANGE OF FLOW SPEEDS BY VARYING EXPOSURE TIME
- USE OF DETECTOR ARRAY ELIMINATES NEED FOR FILM DEVELOPMENT AND CALIBRATION
- DIGITAL OUTPUT ENABLES FAST, CONVENIENT COMPUTER ANALYSIS IN NEAR REAL TIME

Fig. 1 Overview of advanced streak recording for multiple-point 3-D velocity measurement.

with computer leading to near real-time displays), particularly with regard to data processing time, it may suffer from poor resolution. (Although we are using a 100 x 100 array at present, 256 x 256 arrays are now available and even larger arrays are expected in the future.) If high velocity resolution is more important than processing time, then film recording becomes attractive. Tentatively, we plan to test both film and Reticon recording; the latter will at least be attractive during set-up of experiments and for monitoring major features of the velocity field.

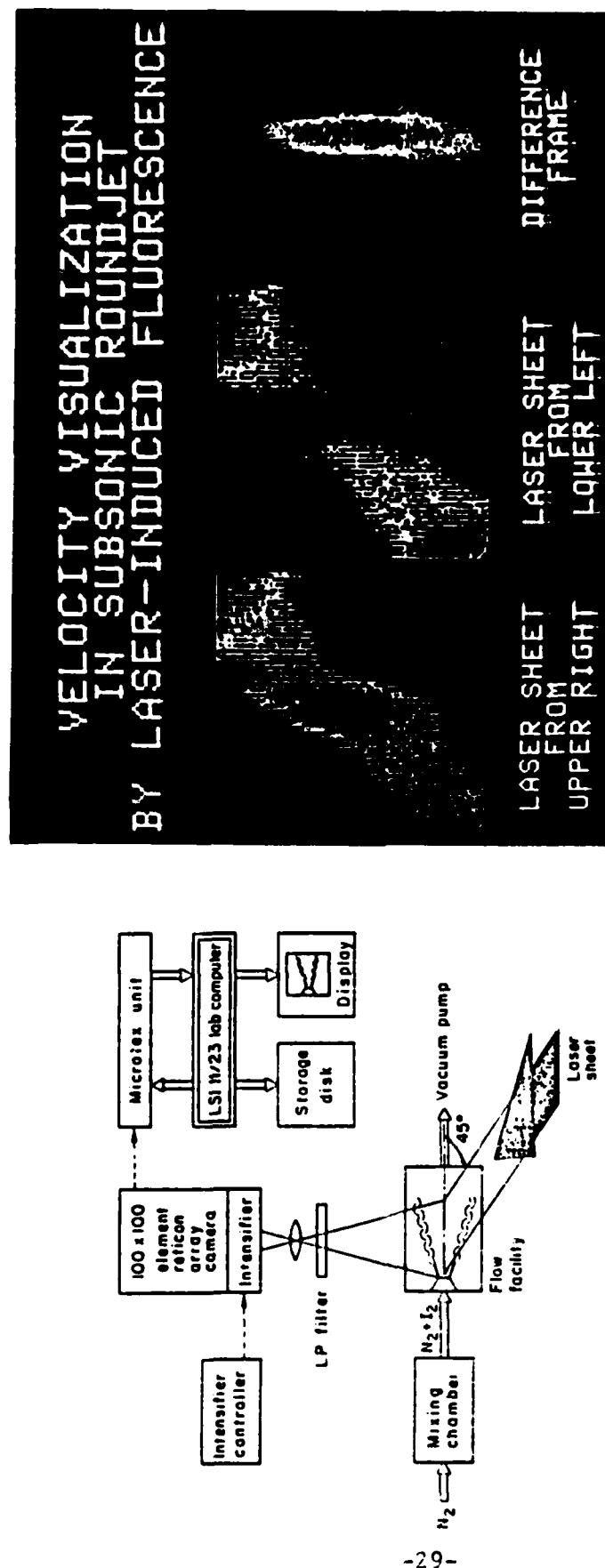
The second scheme under study (see Fig. 2) is based on the Doppler effect and involves monitoring the broadband fluorescence from a sheet-illuminated flow using a Reticon array. The flow is seeded with a tracer species, currently I_2 vapor at about 300 ppm, and a laser source is used to excite a specific transition of the tracer species. The fluorescence from a given flowfield point mirrors the absorption occurring there, which for a uniformly seeded flow depends only on the position of the laser wavelength within the absorption lineshape. Since the absorption line shifts with fluid velocity due to the Doppler effect, the amount of absorption (and hence fluorescence) is a measure of velocity. As this approach actually provides only the velocity component along the laser beam, it is necessary to use multiple beams to obtain the 2-d or 3-d velocity vector.

Scientific Merit

The importance of velocity as a fluid flow parameter is obvious, and so the discovery/establishment of an improved velocity diagnostic offers broad potential for improved scientific understanding of fluid flows. A successful multiple-point diagnostic, in particular, would represent a sufficiently large advance in measurement capability as to enable first-time observations of various flow phenomena and possible discovery of unexpected features.

One of the techniques proposed, based on the velocity modulation (Doppler shift) of molecular absorption lines, offers prospects for a significant improvement over conventional laser Doppler (particle

VELOCITY VISUALIZATION
SIMULTANEOUS MULTIPLE-POINT VELOCITY MEASUREMENTS BY
SENSING DOPPLER-MODULATED LASER ABSORPTION WITH A DETECTOR ARRAY



- o FIRST QUANTITATIVE MULTIPLE-POINT VELOCITY MEASUREMENTS IN A GAS FLOW
- o NO PARTICLE SEEDING REQUIRED
- o NO TEMPERATURE PERTURBATION (AS WITH SODIUM SEEDING)
- o VERY GOOD AGREEMENT WITH THEORY
- o SUPERSONIC AND SUBSONIC FLOWS

Fig. 2 Multiple-point velocity measurements using Doppler-shifted absorption with fluorescence detection.

seeding) anemometry for supersonic flows, flows near surfaces (boundary layers) and flows with high acceleration or deceleration where particle lag is a serious problem.

Status Report

This research is still in its early stages. We have conceived and investigated several promising approaches for multiple-point velocity measurements, and we have selected two of these approaches (described above) for laboratory study. With regard to the streak recording concept, we have researched candidate seed materials and seeding procedures, as well as the electro-optical arrangement to be used (illumination system, optics and detection system), and have now acquired components and seed material (glass microballoons, of about 40 microns diameter).

Our research on velocity-modulated molecular absorption is further along, and in fact the initial experiments for both supersonic and subsonic flows were sufficiently successful that the results have been published. The strategy of the technique is based on detection of fluorescence from a Doppler-shifted absorption line of a tracer species excited by a narrow-linewidth laser source. Iodine (I_2) vapor has been used in the work thus far (because it conveniently absorbs light at visible wavelengths of tunable cw dye lasers), although the method is quite general. Velocity measurements in I_2 -seeded, low temperature flows have now been demonstrated for both supersonic and subsonic cases, using somewhat different procedures. Here we discuss the subsonic approach; details of the apparatus, procedures and results are available in the recent publications cited below.

A sketch of the apparatus employed to monitor velocity in the centerplane of a subsonic nitrogen round jet is shown in Fig. 2. I_2 is seeded at a trace level of about 300 ppm. A sheet of laser light, tuned to a frequency in the wings of an isolated absorption line of I_2 (R(63) line of the (25-0) band at 547.3 nm) is incident at an angle of 45° to the jet centerline. An intensified photodiode array (100 x 100) camera, imaging the plane of illumination, records the broadband fluorescence

emanating from each of the 10^4 imaged locations. The fluorescence signal from each point is proportional to the amount of light absorbed at that point, which in turn depends on the extent of the local velocity-induced Doppler shift of the absorption line relative to the fixed laser frequency. By recording, in quick succession, the signal from forward and counterpropagating light sheets, then taking the difference of these signals at each point and normalizing by the mean, it is possible to establish a simple, direct relation between the signals and the velocity.

We have, in fact, used four sheets of light, i.e. forward and counterpropagating sheets at each of two angles ($\pm 45^\circ$ relative to the jet axis) in the centerplane, to allow determination of the velocity vector in the centerplane of the flow. Although the time required to complete the four measurements was a few seconds in these initial experiments, much shorter measurement times should be possible with a faster method for switching the several light beams.

Sample results of velocity profiles at three axial positions in the near field of the round jet, extracted from the full-field data sets, are shown in Fig. 3. the quantity plotted is the x-component of velocity, U , normalized by the initial value of the nozzle exit velocity, $U_0 = 50$ m/sec. Tests were conducted at various pressures in the range 50-200 Torr, all showing good quantitative agreement with both theoretical calculations and previous measurements using standard techniques.

These data indicate the capability of the 4-beam technique to probe low Mach number flowfields. The negligible level of random noise in the acquired frames suggests that exposure times much closer to the limit set by the maximum framing rate of the camera (500 frames per second) are feasible; the ultimate limit is set by the fluorescence photon flux. The simplicity of the scheme should lend itself to fast on-line data processing. The excellent spatial resolution which can be achieved is an intrinsic feature of laser-induced fluorescence techniques. Further improvements are being directed toward simplifying the experimental set-up and improving temporal resolution. Experiments in combusting flows using naturally occurring or seeded species are planned.

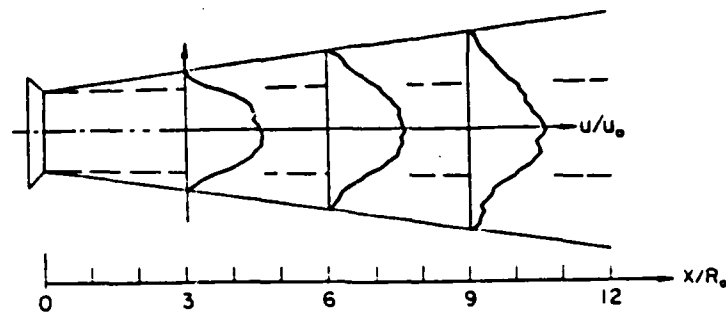


Fig. 3 Flow field of a subsonic roundjet near exit; $U_0 = 50$ m/sec and $P = 50$ Torr. Three velocity profiles, measured with fluorescence detection of Doppler-shifted I_2 absorption at 547.3 nm, are shown.

Publications and Presentations

Presentations

1. J.C. McDaniel, "Velocity Measurement in a Flame Using Doppler-Shifted Laser-Induced Iodine Fluorescence," presented at Thirty-Fifth Meeting of the American Physical Society, Div. of Fluid Dynamics, Rutgers U., Nov. (1982).
2. J.C. McDaniel, "Quantitative Measurement of Density and Velocity in Compressible Flows Using Laser-Induced Iodine Fluorescence," paper 83-0049 presented at AIAA 21st Aerospace Sciences Meeting, Reno (January 1983).
3. B. Hiller, J.C. McDaniel, E.C. Rea, Jr., and R.K. Hanson, "Laser-Induced Fluorescence Technique for Velocity Measurements in Subsonic Flows," presented at CLEO '83, Baltimore (May 1983).

Publications

1. J.C. McDaniel, B. Hiller and R.K. Hanson, "Simultaneous Multiple-Point Velocity Measurements Using Laser-Induced Fluorescence," Optics Letters 8, 51 (1983).
2. B. Hiller, J.C. McDaniel, E.C. Rea, Jr., and R.K. Hanson, "Laser-Induced Fluorescence Technique for Velocity Measurements in Subsonic Flows," Optics Letters 8, 474 (1983).

Personnel

Ronald K. Hanson Professor (research), Mechanical Engineering

James C. McDaniel Postdoctoral Research Fellow, Mechanical
Engineering (Now an Assistant Professor at the
University of Virginia)

Bernhard Hiller Graduate Student, Mechanical Engineering
(Ph.D. Expected June 1985)

2.5 Plasma Diagnostics (Quantitative Visualization)

Introduction

In addition to the diagnostics studies described in other sections of this report, which focus primarily on combustion measurements, we foresee a need for advanced diagnostics to be used in fundamental research on plasmas and in studies of various plasma-related energy conversion schemes.

Primary motivation for this work arises from renewed interest in developing advanced space power and propulsion systems, which may involve plasmas. Among the systems under consideration are thermionic converters and MHD generators for electrical power generation, MPD thrusters and beamed laser energy for propulsion, and direct production (in space) of high-power laser radiation for beamed energy. Considerable research will of course be needed before optimum systems for space utilization are identified, developed and placed in service, and we believe that advanced diagnostics can play an important role in such research. Furthermore, the initiation of work on plasma diagnostics forms a logical, efficient extension of our current program.

In a separate section (2.6), Professor Self describes his research on diagnostic needs for thermionic converters. Here we discuss our initial work to establish quantitative visualization schemes for species concentrations and other plasma properties near electrodes and boundary surfaces. Our interest in quantitative visualization techniques for plasmas stems largely from our recent success with such methods in the context of combustion flows, where the ability to provide added dimensions of information (relative to single-point measurements) has already had substantial impact. In the case of combustion gases, we have employed laser-induced fluorescence (LIF) as the sensing process, and we have chosen to begin with that same process in our plasma diagnostics research, although other processes will also be considered. The major differences between our combustion-oriented visualization work and that being initiated for plasmas are in the composition and conditions (pressure, temperature and velocity) of the plasma systems of interest,

and also in the geometry or configuration of the systems. Of course, the subject of plasma sciences encompasses a very broad range of plasma conditions and phenomena, and so we will have to be satisfied, at least initially, with exploring a modest subset of conveniently accessible plasma parameters involving weakly ionized, low temperature gaseous systems.

Scientific Merit

This research seeks to provide unique new diagnostic methods for use in studies of various plasma properties and plasma phenomena. The merit of our work rests on the growing significance of plasma sciences in connection with Air Force activities and interests, and also on the critical role which advanced diagnostics can play in facilitating basic and applied research in this area. The techniques which we currently plan to pursue are novel and offer potential of significantly enhancing diagnostics capabilities for partially ionized gases.

Status Report

This project is new, having been initiated just this past summer (1983). At present, one graduate student (Mechanical Engineering) and one visiting researcher are participating in this research.

Work thus far has focused on the design and construction of a simple plasma test facility, with good optical access, which will enable us to vary several parameters of interest including gas mixture, pressure, electrode configurations and flow rate, for both steady and transient electrical discharges. The design is now complete and the facility is under construction. In brief, the viewing chamber is a stainless steel box, with windows on all four sides, and electrodes mounted on removable top and bottom plates. The chamber is coupled to an inlet gas manifold, for varying the input gas composition and flow rate, and to a vacuum pump. We have paid particular attention to optical access so that we will be able to demonstrate the ability to measure with high spatial resolution near surfaces (electrodes) and with high temporal resolution in transient discharges. We hope to have the system assembled by the end of 1983, with facility evaluation to begin in 1984.

There is of course a requirement to match the wavelengths of the exciting laser system with the absorption spectra of molecules of interest, and so our initial experiments will be influenced by the tunable laser sources currently in our laboratory. We plan to utilize both our tunable cw dye laser (which can provide narrow-linewidth output in the ranges $\lambda = 280\text{--}310\text{ nm}$, $340\text{--}345\text{ nm}$ and about $500\text{--}800\text{ nm}$) and our tunable pulsed dye laser (broadband output in the range $\lambda = 220\text{--}900\text{ nm}$) as laser sources in PLIF experiments.

Initially we plan to illuminate planar regions of relatively standard, steady and unsteady discharges in low-pressure air, rare gases or various gas mixtures. Detection of the PLIF signals will be by our intensified photodiode array camera. In addition to effort aimed at debugging and characterizing the diagnostics system and test facility for these "standard" discharges, early work will include identification (through literature surveys and laboratory studies) of optimum excitation and detection wavelengths for species of interest.

The outcome of this initial work (which is itself a rather substantial undertaking) will surely influence our subsequent research direction. Tentatively, we are considering three directions of inquiry: (1) exploration of other, less understood types of discharges where PLIF may have special utility; (2) determination of fundamental plasma properties, including spectroscopic and kinetic parameters; and (3) the development of diagnostic techniques for quantities other than species concentration, e.g. electron number density and temperature.

One further emerging aspect of our research plans should also be mentioned, and that has to do with growing interest in radiative coupling between lasers and plasmas, i.e. laser-sustained or -stimulated plasmas. As an example, UV lasers are now being used to selectively influence plasma chemistry, particularly in connection with chemical vapor deposition on surfaces. Once our new high-repetition-rate excimer laser is installed during the coming year, in connection with our flow visualization work in combustion gases, this laser can also be used as a high power source of UV radiation to initiate or perturb a plasma, the behavior or response of which could then be studied using our PLIF

plasma diagnostics system. Working in such an area, namely laser-plasma interactions (or laser chemistry), would provide useful focus for our diagnostic research and also increase both the visibility and potential scientific impact of our plasma-related program.

Publications and Presentations

None.

Personnel

Ronald K. Hanson	Professor, Mechanical Engineering
Jerry Seitzman	Graduate Student, Mechanical Engineering
Fumikazu Itoh	Visiting Researcher, Japan

2.6 DIAGNOSTIC TECHNIQUES FOR THERMIONIC CONVERTER PLASMAS

Introduction

In this reporting period a rather general study was made of the needs and possibilities of new diagnostic techniques applicable to thermionic converter plasmas.

It should be pointed out that the term plasma encompasses an enormous range of parameter space extending from astrophysical plasmas to various types of laboratory gas discharges and plasma devices. As a result a very wide range of plasma diagnostic techniques have been developed over the years that tend to be quite specific to the particular type of plasma under study. Thus, the techniques tend to be specific rather than generic and have been developed in response to the needs of a particular type of plasma or plasma device.

In view of the aforementioned situation, and in view of the fact that the thermionic converter is one of the most important regimes of plasma associated with devices of prime importance to USAF space applications, our attention was focused on the needs for plasma diagnostics related to thermionic converters.

In the first place a rather extensive survey was made of the background literature and the state of the art of thermionic converters. It was rather surprising to find that although the general theory of thermionic converters is rather well developed in most respects, that there has been very little experimental verification of the plasma state internal to converters. Most of the experimental results are obtained as external voltage-current measurements as a function of electrode and reservoir temperatures. Probably the most important reason for the lack of internal measurements is due to the problem of access to the plasma in very small diode gaps.

The problem with relying on comparison of theoretical models and external measurements is that, when there is disagreement, there is no satisfactory method for ascribing the discrepancy to any particular aspect of the theoretical model. All one measures is an overall experimental loss of performance relative to the theoretical model. This loss

is usually described in terms of a phenomenological barrier index although the physical origin of the performance loss is not clearly identified.

On examining the theory of thermionic converters it appears that the weakest link is the modeling of the sheath region. It is quite possible, if not probable, that a significant component of the barrier index loss is due to inadequate understanding of the sheaths at the electrodes. Moreover, no adequate measurements of the potential drops at the sheaths have ever been made.

For this reason, detailed consideration was given to the design of an experimental technique which would allow the sheath field and potential to be measured directly. The basic technique proposed was to use a very fine electron beam fired parallel and very close to the electrode surface and to measure the deflection of the electron beam due to the sheath field. By using an electron beam of approximately 10 kV energy a beam width of 1 micron or less should be achievable, which should be adequate to resolve the sheath potential profile in an operating diode to the desired accuracy to check the theoretical model.

As a backup to this technique it was proposed to measure the sheath capacitance and resistance as a function of frequency. From suitable modeling of the sheath region it should be possible to back out from such measurements additional information regarding the sheath thickness.

The foregoing description represents a brief summary of the study made under this project. A very much fuller account containing a detailed literature survey and justification of the need of the work, and giving much more extensive details of how the work would be implemented was the subject of a pre-proposal submitted to AFOSR.

Personnel

Sidney A. Self
Stephen M. Jaffe

Professor (Research), Mechanical Engineering
Graduate Research Assistant

2.7 APPLICATION OF DIAGNOSTIC TECHNIQUES TO TURBULENT REACTING FLOWS

Introduction

A principal motivation for the development of advanced diagnostic techniques for reactive flows is the need to characterize flowfields in practical combustion devices. One component of the present overall program is the development of a laboratory-scale facility which simulates essential features of practical combustion devices and therefore provides a useful test facility for the evaluation of various diagnostic techniques. This facility is now available and is being used to evaluate several optical diagnostic techniques as well as to obtain flowfield data on flows of fundamental interest.

The flow configuration currently available is an atmospheric-pressure, two-dimensional shear flow, Fig. 1. This facility provides a means of simulating fuel-air mixing regions in air-breathing engines. The non-reacting flow field in this facility has been characterized by conventional diagnostic methods, such as hot wire anemometry, and work is underway to incorporate some of the diagnostics being developed in other parts of this program. Two different diagnostic techniques are being explored at the present time: a fiber optic probe for time-resolved point measurements of species concentration, and the planar laser-induced fluorescence flowfield visualization technique described in Section 2.3. An essential element of this study is the development of computer-based methods for quantitative reduction of the flow field data obtained from the two methods.

Scientific Merit

The evaluation and validation of advanced diagnostic techniques in well-characterized turbulent reacting flows is an important final step prior to transfer of technology to outside users. Furthermore, computer-based methods for reduction of flow field data are required to provide quantitative information on the reacting flow field structure. In the appropriate form, these data may be applied both to characterize specific reacting flowfields and to model and predict general classes of turbulent reacting flows.

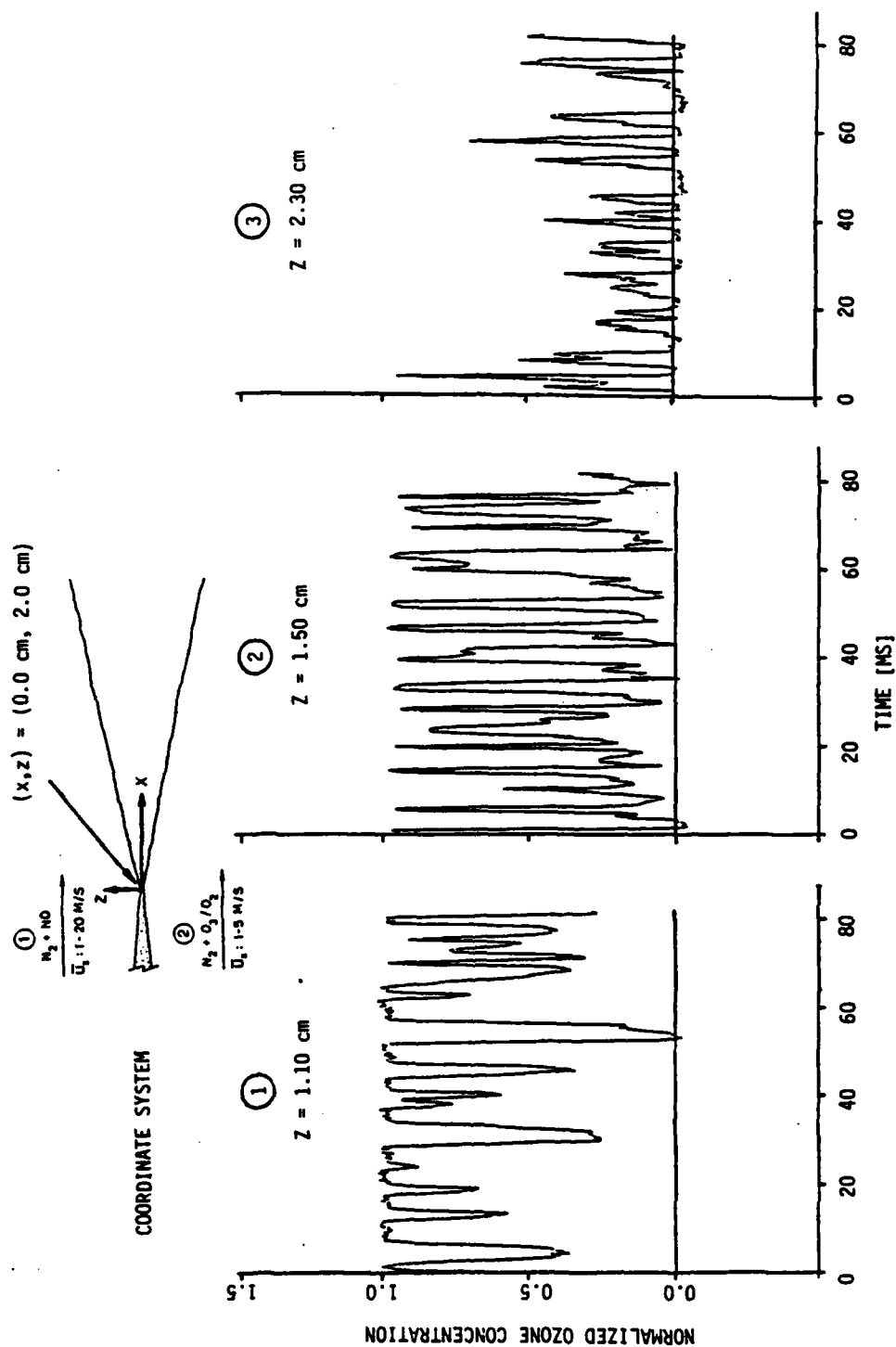


Fig. 1 Ozone concentration time histories: Non-reacting flow case ($x = 11 \text{ cm}$)
 $U_1 = 6 \text{ [m/s]}$, $U_2 = 3 \text{ [m/s]}$; freestream O_3 concentration = 1100 ppmv.

Status Report

Extensive fiber optic probe measurements have been conducted in the two-stream mixing layer. Selected reacting and non-reacting flow cases were investigated. Experimental conditions were chosen so as to properly evaluate the operational characteristics of the diagnostic, as well as provide insight into the structure and dynamics of the turbulent reacting mixing layer.

The fiber optic probe simultaneously monitors absorption by two species, thereby providing real-time concentration data at a particular location in the flow. It can be shown that simultaneous measurements of these two species provides a complete description of the concentration field in the reacting mixing layer.

Computer-based techniques for processing the available experimental data are currently being employed to provide the statistics of both the non-reacting and reacting flow. The quantities of interest include the expectation values, variances, probability density functions (pdfs), spectra, intermittency factors, and correlations of the concentration variables. Representative data are included in Figs. 1 and 2.

The concentration time histories of a non-reacting species, O_3 , at various locations in the flow, Fig. 1, are consistent with the accepted view of the mixing layer; the regular variation in the concentration indicates the presence of large-scale coherent structures. These traces also reveal a striking degree of 'unmixedness' throughout the layer. Well-defined, intermediate concentration levels occur infrequently at all three locations.

The concentration pdfs which correspond to the data in Fig. 1 are represented by the green curves in Fig. 2. These pdfs indicate the presence of two distinct regions in the mixing layer: completely unmixed fluid from either freestream, entrained by the large structures into the layer (the peaks at 0 and 1), and an interfacial diffusion zone where mixing has occurred at the molecular level. The fluid in this diffusion zone is rapidly depleted by a chemical reaction which consumes O_3 , cf. the red curves in Fig. 2. The pdfs of the reacting flow are dominated by

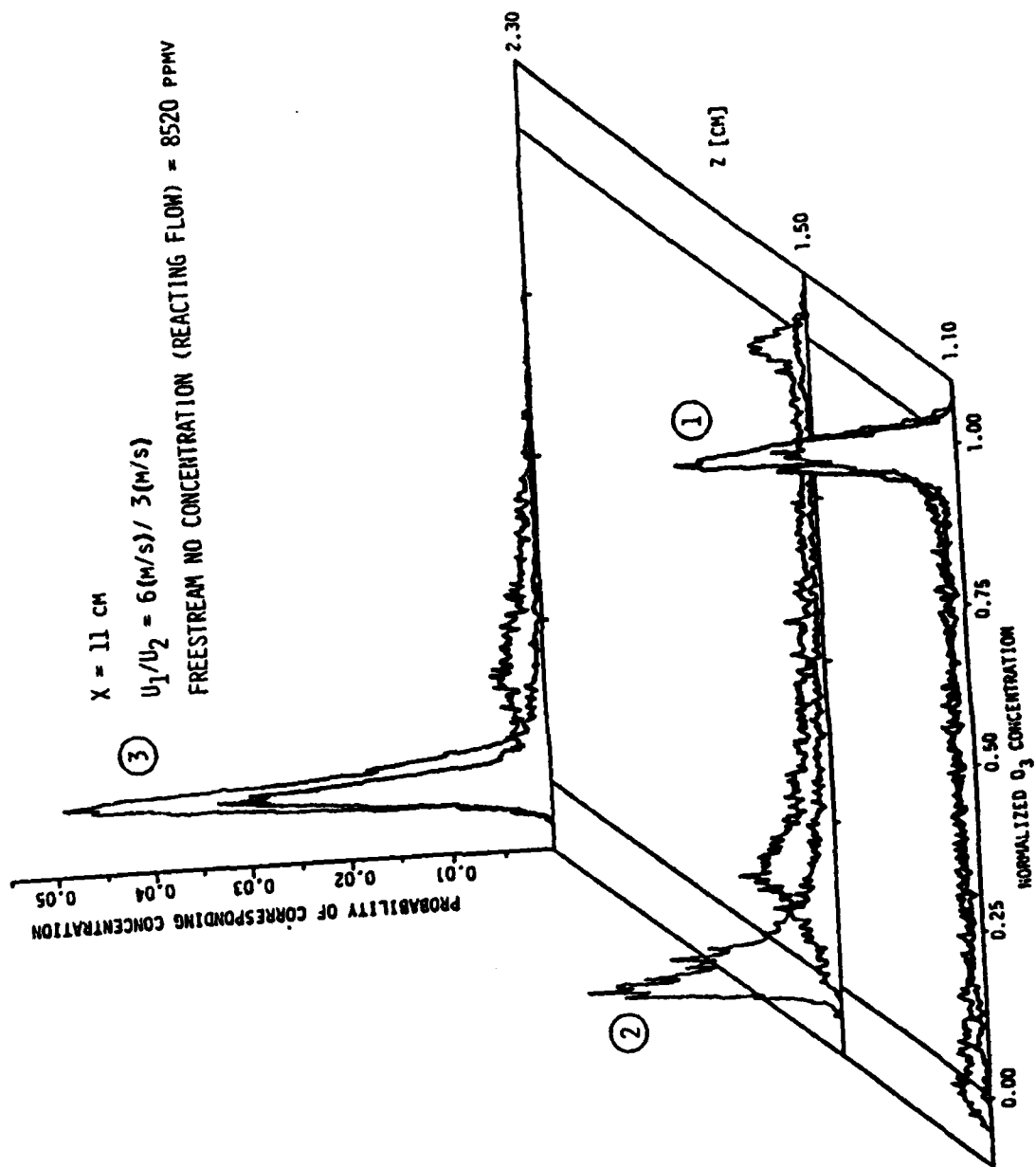


FIG. 2 COMPARISON OF NON-REACTING AND REACTING (RED) O_3 PDFs

the peaks at 0 or 1, with almost negligible probability associated with intermediate values of concentration.

In addition to the optical probe measurements, experiments employing the planar laser-induced fluorescence (PLIF) technique have been performed* in a non-reacting mixing layer. Here, a tracer species, NO, is pumped with the appropriate resonant laser radiation and the resultant fluorescence signal is monitored with an enhanced 100 x 100 photodiode array. An instantaneous planar view of the NO concentration field is presented in Fig. 3. In this picture, we can easily detect the large-scale structures of the layer. As suggested by the probe data, the mixing layer appears to consist of regions of unmixed freestream fluid and the interfacial diffusion zones. Future experiments are being planned to extend the PLIF measurements to the reacting flow situation.

Publications and Presentations

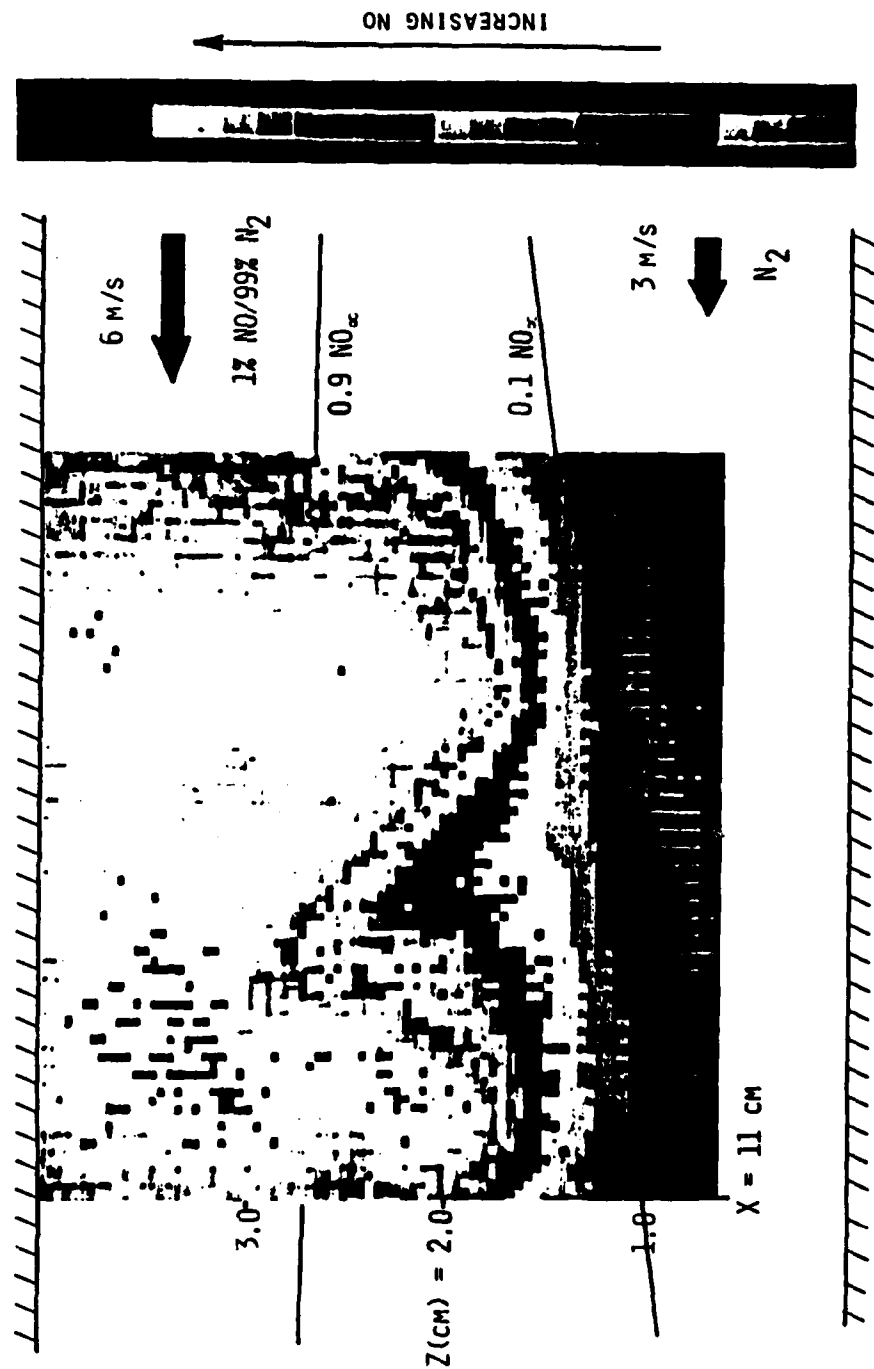
1. S. M. Masutani and C. T. Bowman, "A Fiberoptic Absorption Probe for Measurement of a Conserved Scalar in a Non-Premixed Turbulent Reacting Flow," paper 82-62 at Western States Section/Combustion Institute Meeting, Livermore, CA, October (1982).

Personnel

C. T. Bowman	Professor, Mechanical Engineering
Stephen M. Masutani	Graduate Student, Mechanical Engineering (Ph.D. expected June 1984)

* The effort of G. Kychakoff, R. Howe and R. Booman of Professor Hanson's group in setting up and operating the PLIF system is gratefully acknowledged.

FIG. 3 PULSED L-I-F PLANAR FLOW VISUALIZATION IN A NON-REACTING MIXING LAYER



2.8 CONCENTRATION MEASUREMENTS IN EVAPORATING FLOWS

Introduction

A wide variety of combustion devices rely for their operation on the evaporation and mixing of liquid droplets in the presence of turbulent flow. For example it has been observed that ignition delay times in gas turbine combustors may often be correlated with droplet evaporation times. Results of this sort have motivated many investigators to incorporate the evaporation process into models of turbulent combustion. However, the behavior of droplets in a turbulent combusting flow is extremely complex involving simultaneous heat, mass and momentum transfer. Consequently, models of spray combustion are often required to compute very detailed results for combusting flowfields without benefit of experimental data for comparison.

The research described here involves development of a new diagnostic technique for measurement of droplet evaporation rates under controlled laboratory conditions. The aim is to develop a spatially and temporally resolved technique for measuring the concentration field around evaporating drops in an unsteady flow. At the present time, laser induced fluorescence using iodine as a fluorescent seed material appears to be the best choice for the measurements.

In our current approach, octanol alcohol with iodine in solution is introduced in a gas flow in droplet form and as the solution evaporates laser induced fluorescence from the iodine molecules is used to study the evaporation process. Fluorescence allows point measurements to be made in a general non-steady three-dimensional flow by using a focused laser beam to excite the fluorescing molecules and collection optics to select a particular segment of the beam path. Because evaporation can be studied as a constant pressure process, quenching of the fluorescence signal does not complicate data analysis. Verification of the technique developed for these studies will be carried out in a unique flow facility designed to operate over a wide range of pressure, particularly subatmospheric pressure appropriate to diagnostic techniques based on laser induced fluorescence.

Scientific Merit

Improved knowledge of the physical process by which molecules leave the liquid state of a fuel droplet and diffuse or mix with the gas environment is needed in order to better understand the physical processes of spray combustion. In particular, one needs multipoint measurements of the vapor concentration field in the neighborhood of a droplet evaporating in an unsteady flow. At present, no technique has been developed to give this information. The aim of the present research is to develop a spatially and temporally resolved technique based on laser induced fluorescence for measuring the concentration field around evaporating drops in an unsteady flow.

Status

Considerable progress has been made in the last six months in achieving our objective of developing a technique to measure the vapor concentration field about a single evaporating droplet. One of the principal reasons for the progress is that we decided to first work with a single droplet supported on a very fine hypodermic needle, and then turn attention to a freely falling droplet after we had refined our method. The technique we initially employed is depicted by the diagram in Fig. 1. The droplet is formed and allowed to grow on the tip of a very fine hypodermic needle, drawn from a quartz tube to a diameter of about 100 μm at the tip of the needle; and as the vapor cloud forms about the droplet, it is continually carried away by a low-velocity background gas, so that the vapor does not saturate the entire enclosing volume. A sheet of argon-ion laser light is used to illuminate a given transverse section of the vapor cloud, as shown, and detection optics are focused onto the section to record and observe the fluorescence intensity in the cross section. In these experiments we used droplets formed from a solution of iodine in octanol, where iodine is the fluorescing specie used to tag the octanol vapor.

The four photographs displayed in Fig. 2 are representative of the conditions that can now be studied with a captured droplet. One view (upper left-hand corner) shows the laser sheet placed in front of the

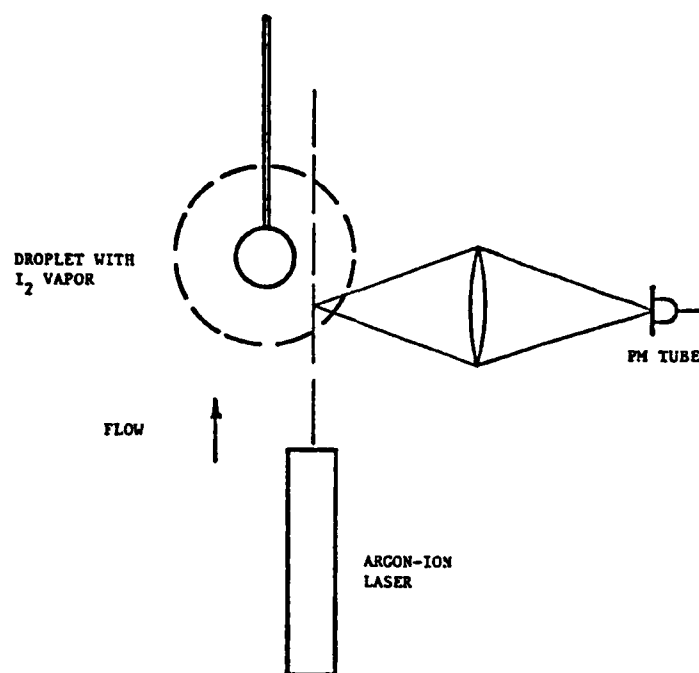


Fig. 1 Schematic arrangement of experiment for the study of droplet evaporation with a captured droplet.



Fig. 2 Iodine fluorescence near an evaporating droplet of octanol with iodine solution.

droplet and at a very early stage in the droplet formation, when the droplet and vapor cloud are both quite small, while the view below it shows the droplet at a later stage, after it has grown in size, and with the laser sheet positioned behind the droplet. The back-lighting provided by the luminous transverse section gives a clear outline of the droplet, the quartz hypodermic needle, and a small shadow where the laser sheet strikes a portion of the droplet. The work has shown that small droplets first form above the tip of the needle, because of surface tension effects; then as they grow in size (up to 1 mm in dia.), their mean position lowers and they finally fall from the tip. The two remaining photographs in the figure are for still later stages where the droplet and vapor cloud have grown considerably. Also, the laser sheet is positioned nearly on the droplet central section, giving a full sized shadow.

Two very important observations are made from these photographs: (1) the droplet itself is black indicating that the scattered laser light can be filtered very effectively, because it is at a different wavelength than the fluorescent light; and (2) the shadow is also black showing that good contrast can be gotten between regions of no fluorescence and regions of fluorescence, where data are to be collected. These photographs confirm that our original concept of photographing evaporating droplets is a valid one, and that it is also becoming a very practical one.

Figure 3 shows an isometric view of the vapor concentration field about a single droplet and shows that the technique leads to a quantitative measure of the concentration distribution in a single plane. At this stage we are less concerned with linearity and calibration constants than with the development of the method and therefore we view the diagram as a good approximation to the actual concentration distribution. Once the data shown in Fig. 3 are available, it is then possible to construct false-color displays of the distribution, as shown in Fig. 4. In the photograph, red represents the highest concentration of vapor and blue the absence of vapor, with three colors for intermediate levels. The color display clearly shows the droplet shadow to the left

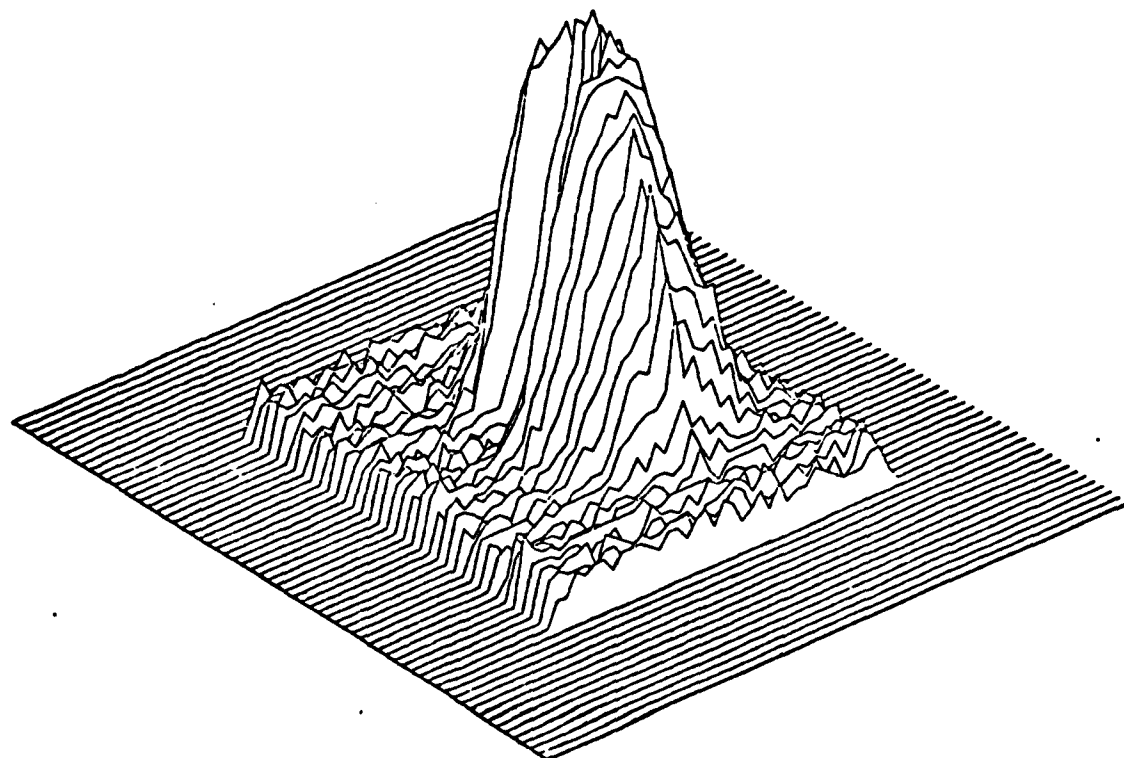


Fig 3. Vapor concentration in a cross-section plane near an evaporating droplet.



Fig. 4. False-color display of the vapor concentration field near an evaporating droplet.

(in blue), a hint of the supporting needle at the top, and the effect of the vertically rising background gas (nitrogen) by the bow-wave shape of the bottom of the cloud. The data processing required to produce Figs. 3 and 4 was carried out in Professor Hesselink's Digital Image Processing Laboratory, who kindly made available both laboratory facilities and time to generate these views.

Following our work in photographing the droplets, we substituted the still camera with a laboratory TV system consisting of a Vidicon camera, tape recorder, and monitor. The substitution proved to provide a significant improvement in ease of use, greater sensitivity, and opportunity for improving the quantitative aspect of the study. The system operates at 60 frames per second and can be used in a stop-action mode. The large view that is displayed on the screen, and the increased sensitivity to light which the system provides, make both the set-up and study of the evaporating process much easier to carryout.

With the TV monitor we are able to observe the fluorescence about a falling droplet and capture the scene on tape for later detailed analysis. Because of this capability, our work has now progressed to a study of a freely falling droplet, which is rapidly preparing us to make use of the flow facility we have constructed, as well as provide us with new ideas on its use. Our work with the falling droplet has progressed to the stage where a sequence of views is first recorded on tape and then an individual frame is selected and analyzed for its information content. Within an individual frame, we are able to select and display in an oscilloscope the intensity distribution along a single raster line, using special electronics we have developed for this purpose. Figure 5 gives an example trace showing the kind of data we are now able to collect in this mode. The trace shown in Fig. 5 represents the same data as that shown in Fig. 3, if one were to slice the view with a plane along one of the axes. However, the difference in time required by the two procedures is vastly different because film processing time is not a factor when the video tape is used. Also, the control on the linearity of the Vidicon tube together with its calibration is far easier to manage than photographic negatives.

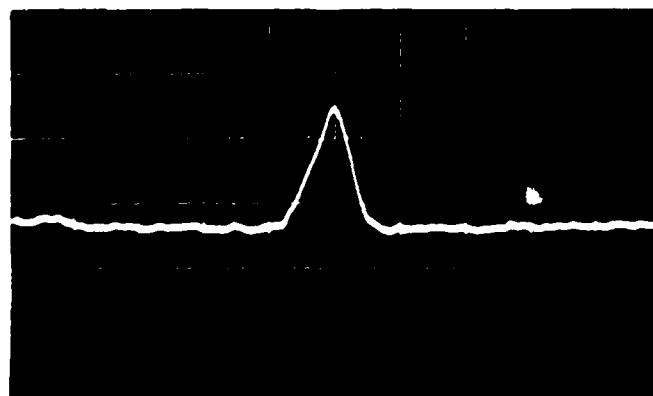


Fig. 5 Distribution of vapor concentration along a single raster line from a TV display of a falling droplet.

The work has reached a very productive stage and most of our immediate efforts will be directed towards the collection and study of data which our method provides. Considerable effort has been expended in developing the technique and learning how to refine the approach. We are now in a position where our confidence is quite high and are eager to establish the usefulness of the method.

A logical next step in the application of the diagnostic technique is to study evaporation of a droplet stream under flowing conditions using the variable pressure facility constructed for this project. In preparation for the experiments using the fluorescence technique we have followed two lines of effort. The first involves gaining some experience at photographing small ($\sim 40 \mu\text{m}$) droplets generated by the Berglund-Liu atomizer. In Fig. 6a the drops are illuminated by a pulsed source produced by switching on and off a Bragg cell attached to a cw argon ion laser. The continuous main output beam is blocked while the pulsing first order output beam is used to backlight the droplet stream. The picture represents 40 exposures of the drop stream and confirms the periodicity of the droplet generation process.

The second line of effort involves developing a controlled flow into which the periodic stream of droplets will be injected. The approach being used is to generate a periodically excited co-flowing jet which

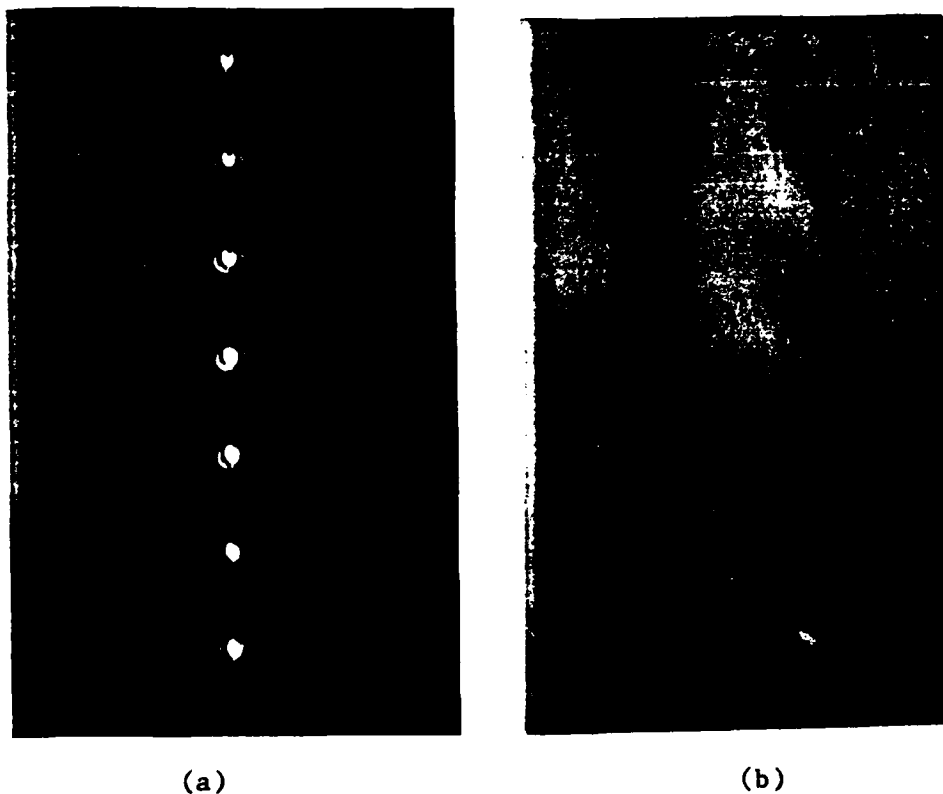


Fig. 6 (a) 40 exposures of a periodic droplet stream from the monodisperse aerosol generator; (b) 100 exposures of a periodically excited methane-air diffusion flame.

can be synchronized with the droplet stream. If this can be accomplished then it should still be possible to photograph the droplets in the presence of the imposed flow. There is a considerable body of literature on periodically excited cold jets with and without co-flow and it is well known that at low Reynolds numbers extremely tight control of the jet eddy structure can be achieved. However we wondered whether good control could also be achieved in the presence of combustion. Figure 6b shows a Schlieren picture of 100 exposures of a periodically excited methane-air diffusion flame produced using a small jet apparatus in our lab with an internally mounted loudspeaker. We have looked at several excitation frequencies, tube diameters and jet speeds to find an optimum Strouhal number for controlling the flow and find that, as in the cold flow case, extremely periodic behavior can be induced. The next step is

to combine the droplet stream with a co-flowing jet in the facility test section to establish whether the drops can be synchronized with the flow and to implement the diagnostic technique, first under non combusting conditions and then later under combusting conditions. In the latter case the technique can provide information on the evaporation of droplets during the heat up process prior to entry into the flame zone.

Publications and Presentation

Presentation

1. D. Baganoff, "Prospects for Flow Measurements Based on Spectroscopic Methods," International Symposium on Recent Advances in Aerodynamics and Aeroacoustics, Stanford, CA., August 1983.

Publication

1. D. Baganoff, "Prospects for Flow Measurements Based on Spectroscopic Methods," in Recent Advances in Aerodynamics and Aeroacoustics, Springer-Verlag, in press.

Personnel

D. Baganoff	Professor, Aeronautics and Astronautics
B. J. Cantwell	Professor, Aeronautics and Astronautics
A. W. Strawa	Graduate Student, Aeronautics and Astronautics
D. R. Neal	Graduate Student, Aeronautics and Astronautics
U. Ackermann	Visiting Foreign Scholar, DFVLR, Berlin

2.9 THREE-DIMENSIONAL FLOW VISUALIZATION (HOLOGRAPHY)

Introduction

Non-reacting and reacting turbulent flows are inherently three-dimensional in nature. That is to say, flow parameters such as velocity, temperature, density or species concentration are all functions of three space coordinates and also time. The temporal character is often eliminated by averaging the appropriate equations over time, either by using a Reynolds averaging technique or by introducing similarity variables in order to make the flow as steady as is possible. Recent developments in the field of turbulence research indicate that large-scale coherent motions play an important role in turbulent flows. These structures are inherently three-dimensional in extent, and many investigators now believe that a Lagrangian description of the motion of these structures may provide very valuable information that hitherto has been hidden by the more traditional Eulerian approach. The Eulerian approach is simpler and more easily accessible by experimental techniques and it has in the past provided valuable engineering data. However at present no satisfactory physical model exists that can explain or predict many of the experimental observations. For instance, it is not possible to compute the spreading rate for a turbulent jet or the entrainment rate from first principles. Numerical solutions to the Navier Stokes equations cannot be obtained for many practical problems of interest, because of machine limitations. Recently it has been suggested that perhaps our understanding of turbulent flows may be improved by modeling on a computer the behavior of these large-scale vortical motions and their interactions. These new models will have to rely heavily on experimental data either for their input or for comparison with results. Therefore it has been the aim of many researchers in the field to develop diagnostic techniques for obtaining quantitative, instantaneous flow measurements in a plane or in a volume.

In the proposed research a cross section of the object is illuminated by a coherent sheet of light and scattered radiation is collected on film or a two-dimensional detector array as shown in Fig. 1. Three-dimensional data are obtained by translating the sheet of

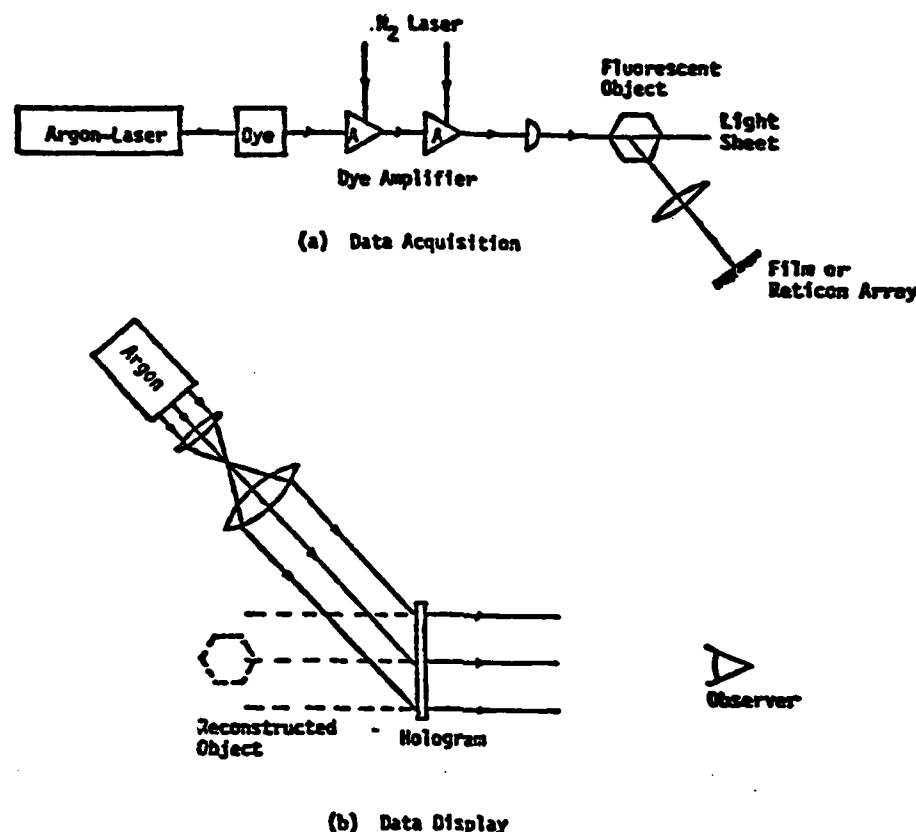


Fig. 1 Experimental configuration for three-dimensional flow visualization project.

light perpendicular to its surface. Ultimately four-dimensional Lagrangian data can be obtained by collecting volumetric data as a function of time. The acquired data, which can represent information about flow parameters such as velocity, density, temperature or species concentration, are then manipulated in a digital computer or a coherent optical processor for display and data reduction purposes. The display technique is based on a holographic method to give true depth perception. (See Fig. 1)

Holography certainly is a competitive method for obtaining three-dimensional flow information, but is restricted to objects that diffusely scatter the incoming coherent radiation. The proposed method is superior to holography for the data acquisition phase of the method, because it is more generally applicable and has greater promise to provide quantitative information about density, species concentration or

temperature fields. At present several efforts are underway at different universities and government laboratories to develop optical probes for measuring density, temperature, and velocity either at a point or in a plane. The main thrust in these projects is related to developing a suitable detection method using either fluorescence, Mie scattering, Rayleigh and Raman scattering or other scattering processes.

In the proposed research, the scattered radiation is recorded either on film or on a two-dimensional reticon photo detector array. The film has to be digitized before any processing of the data can be performed, and the film recording processes are inherently nonlinear, but proper processing can account for these non-linearities. A more direct method involves the use of a two-dimensional array of photo detectors. Presently an array is commercially available that has 10,000 elements and produces a video signal that can be interrogated at a rate of 10 MHz. The dynamic range and sensitivity of the detectors compare favorably with the parameters for film. The reticon array will be used in this project for both data acquisition and digitization of the film.

The data display technique involves the use of holography to obtain three-dimensional perception. The development of three-dimensional display techniques is a very active area of current research, due to the almost universal need to display three-dimensional objects. At least three distinct methods have been suggested, namely the vibrating mirror concept, the display of computer calculated views and the holographic method presented here. Of these methods only the first and the last one are capable of providing truly three-dimensional information. The first mentioned method involves the use of a video display and has no hard copy equivalent and requires an unusually high information bandwidth. The data handling problem will become prohibitive, at least for now, when time resolved volumetric data are considered. Holography certainly has the promise of being superior to either of the above mentioned alternatives, in terms of both information content and three dimensionality. The emphasis of the proposed project will be to manipulate the data obtained in fluid mechanics experiments into such a form that it can be displayed in three dimensions. Several holographic techniques

will be investigated including multiplex, wide viewing angle and phase holograms. This effect will require substantial software development as well as optical processing. For this purpose a VAX 11/780 computer, an image processing facility and some input and output devices are available as well as general purpose image processing programs that were developed by the principal investigator during previous image processing work.

Scientific Merit

A novel diagnostic technique is proposed for measuring fluid properties in three dimensions. The feasibility of the measurement technique is tested using a stationary object. The new method, once developed, should make it possible, for the first time, to determine the instantaneous topology of the large-scale coherent motions known to dominate turbulent flows. The display technique uses holography and is of a general purpose nature. It has the ability to display three-dimensional objects as a function of time at a rate that can be optimized to suit the human observer. In particular it is possible to view and enhance interesting aspects of the object by properly processing the digital data.

Status Report

During the initial contract period, when no student support was available, emphasis was placed on investigating the properties of the holographic display technique, and to write general purpose image processing software for data reduction of combustion data. In October of 1983, John Pender a graduate student working towards a Ph.D. degree in Applied Physics, joined the group and has actively participated in the research. Progress made during the present grant period include the following:

I. Data Acquisition

The wake flow behind a circular cylinder has been visualized in Professor Cantwells' droplet evaporation facility. Two stationary sheets

of laser light oriented perpendicular and parallel to the mean flow direction are used to illuminate a particle laden flow. Smoke is injected into the flow around the cylinder from two slots parallel to the cylinder axis and located at 45 degrees with respect to the front stagnation line. The scattered radiation from the two perpendicular laser sheets is simultaneously recorded on film with a high speed motion camera. Sequential frames in the movie thus represent planar cross-sections of the three-dimensional streak line pattern made visible by smoke tracers.

Secondly, a laminar premixed methane-air flame seeded with sodium has been illuminated with a sheet of laser light perpendicular to the mean flow direction above the flame holder. The laser light is tuned to the sodium-D line and the fluorescent radiation is stored on a high speed motion film. The intensity on the film represents the number density of the seed gas, and provides information about the structure of the flame.

II. Data Processing

- Software has been developed to generate video stereo pairs of the stack of planar cross-sections. This allows us to investigate the effect of applying several sophisticated image processing procedures to the data, before making a hologram. The software is capable of producing revolving views of the data and it gives the observer the impression of walking around the object.
- Development of software for processing and display of three-dimensional data is being carried out in several areas of science and engineering research. However, we have found that progress made in those areas cannot be directly carried over to combustion research without making substantial modifications. For instance, we have obtained extensive experience with the display of three-dimensional medical data and have found that display techniques designed for the display of this imagery gives very bad results when applied to combustion data. Medical

images often contain both sharp edges (associated with bone structure, for instance) and soft tissue whereas combustion data representing densities tend to vary smoothly as a function of position. Consequently new techniques need to be used for finding edges or contours; these high frequency cues are very important for stereo viewing.

- Several edge detection algorithms have been applied to the smoke visualization data. These data are quite smoothly varying functions of position and contours are not easy to locate. We have tried very sophisticated techniques, including a state-of-the-art panel technique, in which the local radius of curvature of the data is calculated.
- An example of the capabilities of our software is shown in Fig. 2. The image represents frame 15 of our sequence of 23 images of half a shedding cycle in the wake behind a circular cylinder. When an edge detection algorithm such as the Laplacian operator is applied to the image the results is very poor indeed, as shown in Fig. 3. The noise amplitude has been substantially increased and edges are difficult to discern. Pre-processing is needed to improve the results. In Fig. 4 we show a result when the lower 40% and the upper 30% of the pixel amplitudes are clipped and the region of amplitudes inside these boundaries is again expanded to cover the full dynamic range. The background is uniform (blue represents zero amplitude) and we have checked that no actual data has been removed. Several isolated noise specks are still present and these can be conveniently removed using a median filter as shown in Fig. 5. Edges can now be extracted by applying to the pre-processed image the Laplacian operator or a directional operator such as the north and south masks. Results are shown in Figs. 6, 7 and 8 respectively. The edge enhanced images are then used as input to the display algorithms.

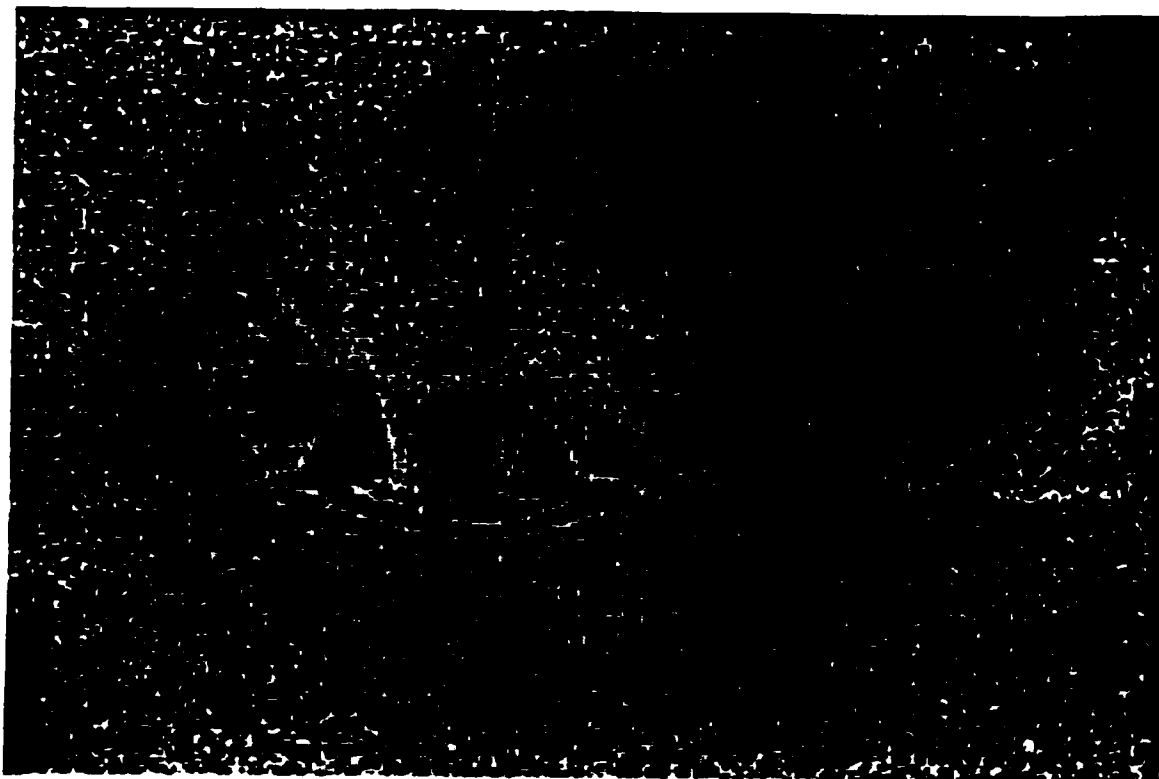


Figure 2. Original image (frame 15).

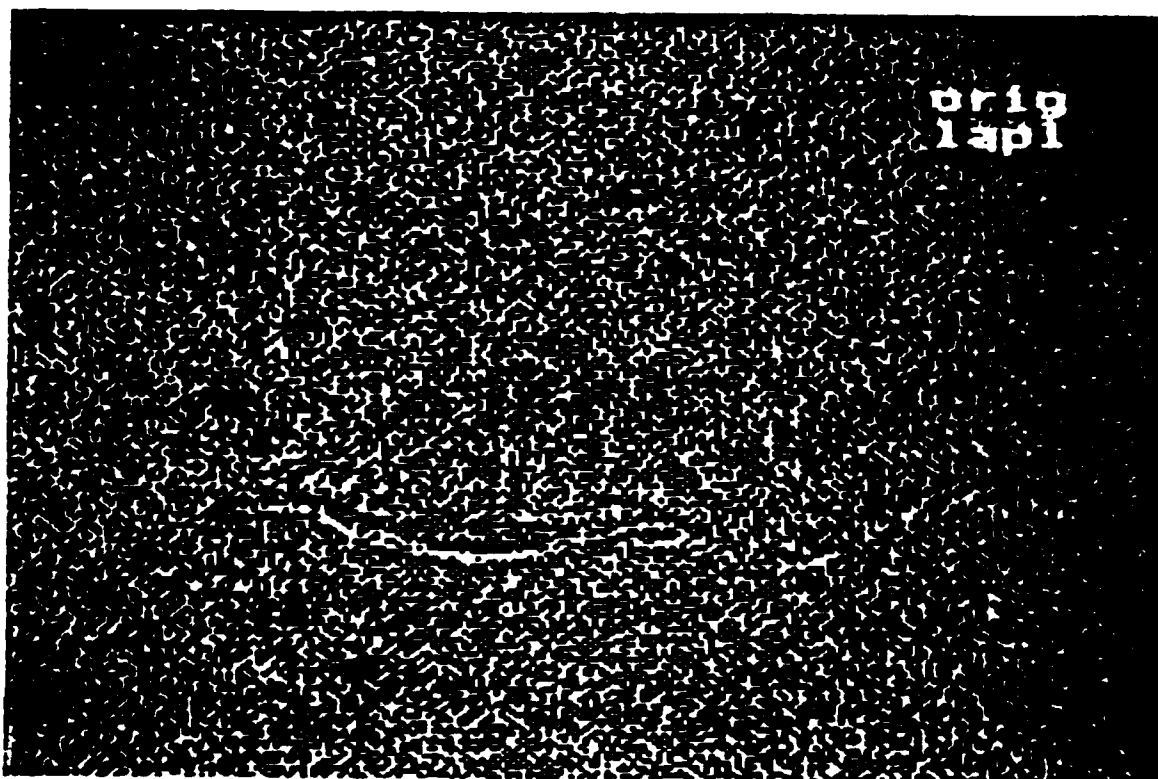


Figure 3. Edge enhanced image using
Laplacian operator.

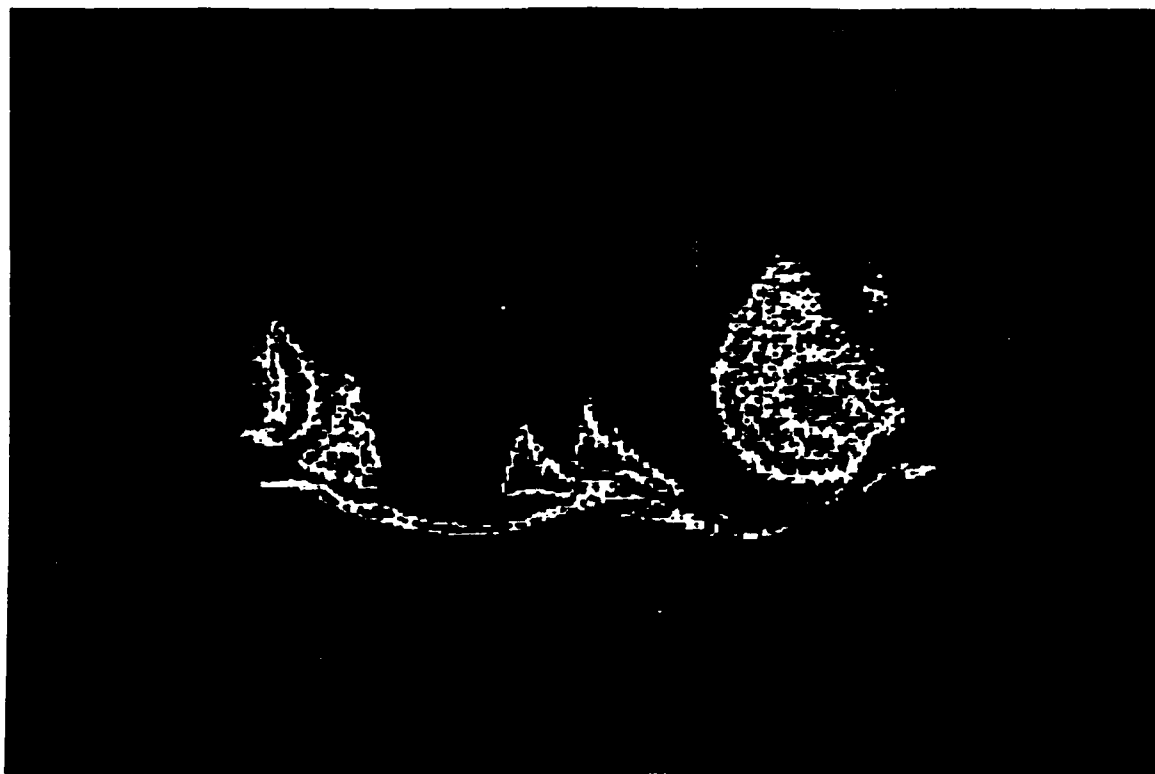


Figure 4. Clipped and stretched image.

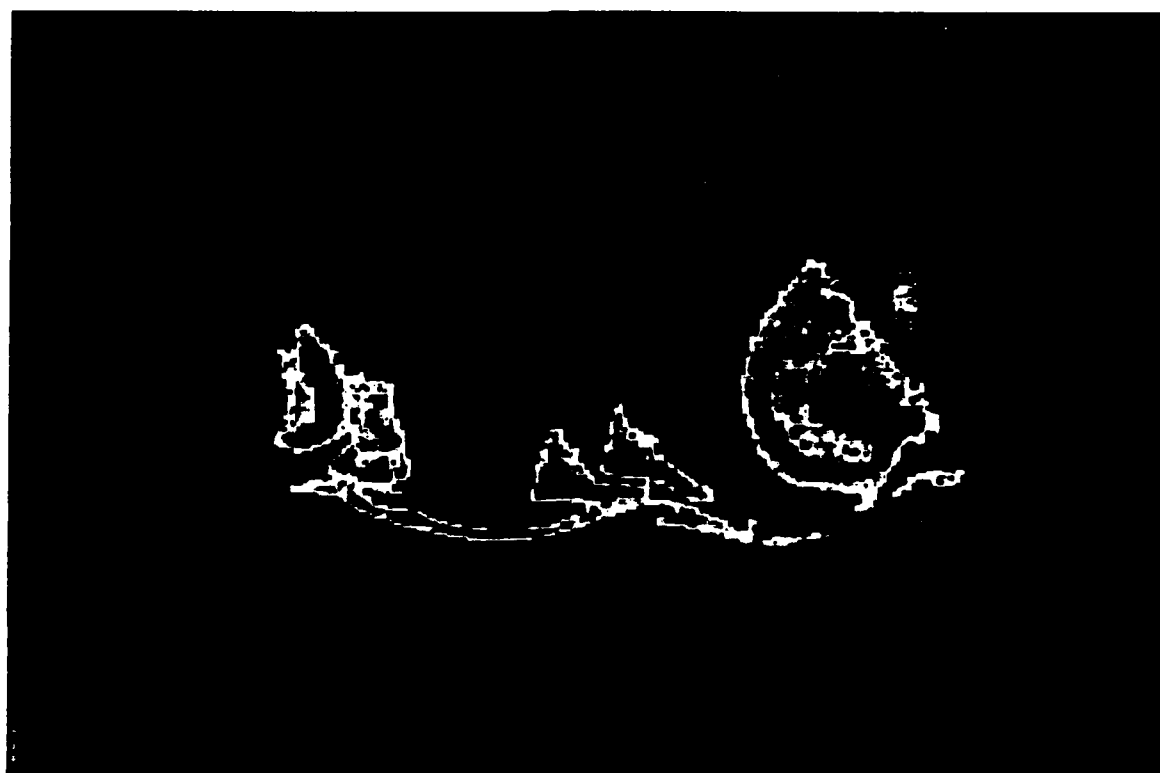


Figure 5. Clipped, stretched and median filtered image.



Figure 6. Edge enhanced image using Laplacian operator on pre-processed data.

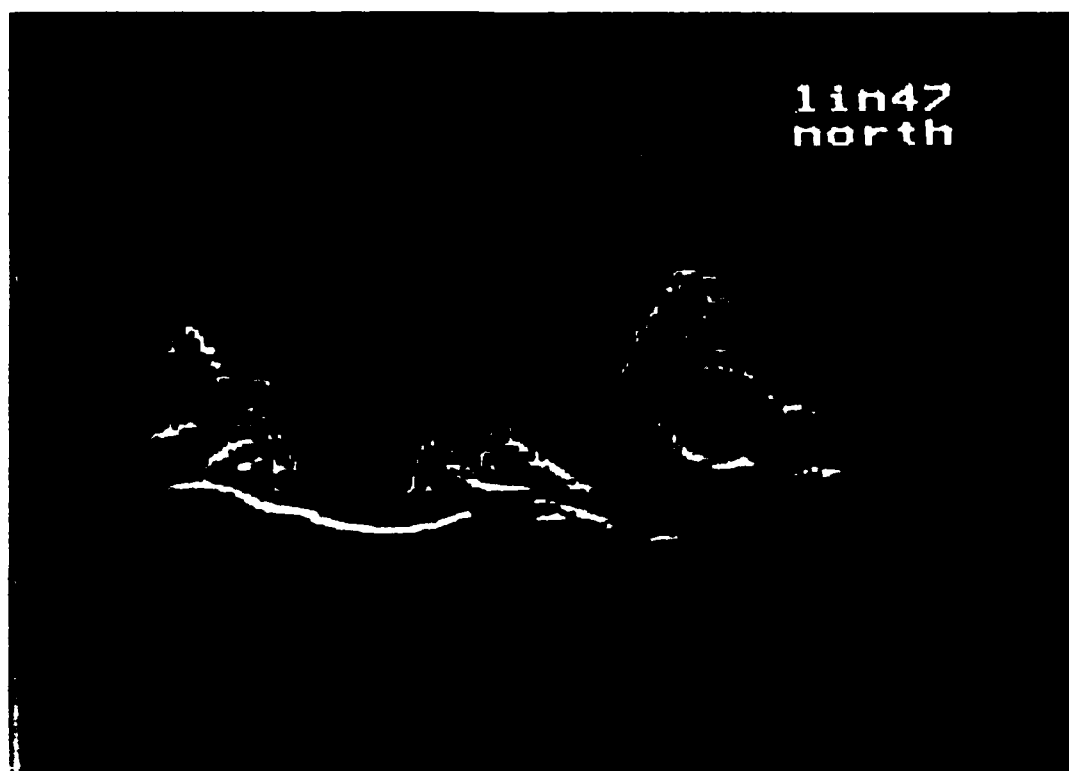


Figure 7. Edge enhanced image using directional edge finder (north).

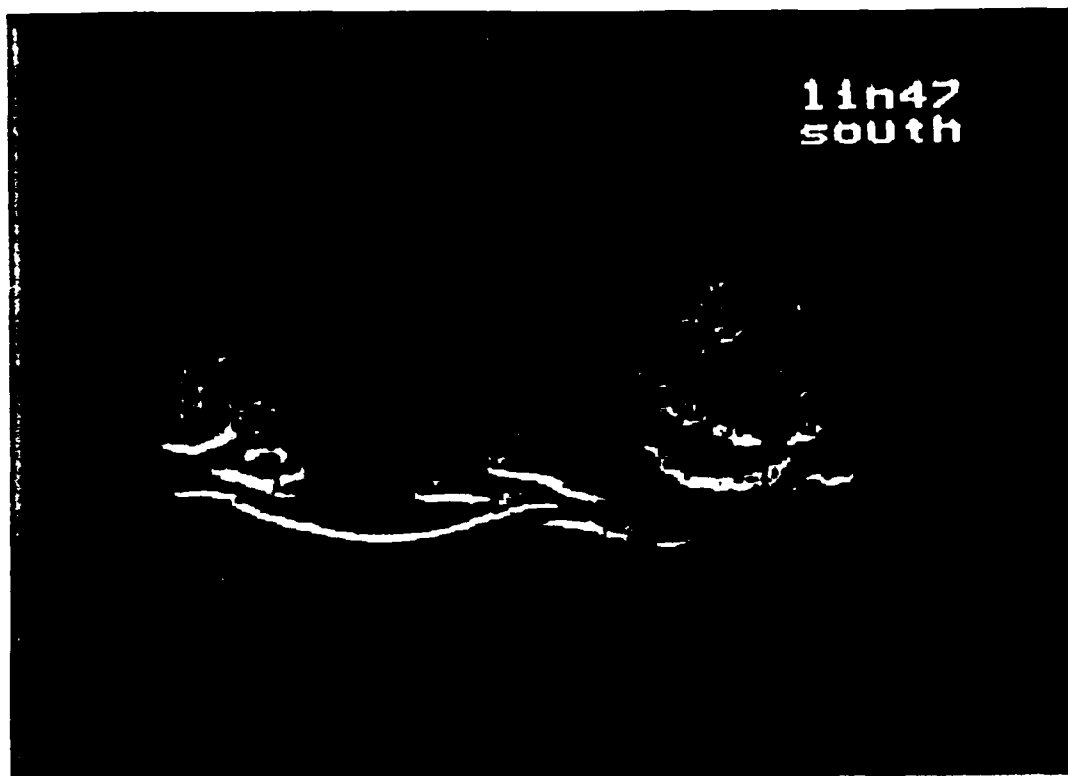


Fig. 8 Edge enhanced image using directional edge finder (south).

- The project for making a multiplex hologram from the data have been completed and a hologram has been made. This, to the best of our knowledge, has not been done before. In addition we have made dynamic video stereo displays of this flowfield.
- Substantial interest has been expressed in this technique during the Third International Symposium on Flow Visualization held at Ann Arbor, Michigan in September 1983. In particular representatives from the Air Force at the Flight Dynamics Laboratory at Wright-Patterson AFB want to use the technique to display auto-stereoscopically the output of three-dimensional numerical calculations. Also, researchers at NASA-Ames want to use the technique for the display of output of their calculations. Presently we are processing a three-dimensional scalar field for the purpose of displaying the results using our

multiplex holographic technique. The display method should make it possible for the first time to examine, both quantitatively and qualitatively, the topology of hairpin vortices in the boundary layer of channel flow. At present no other suitable quantitative diagnostic technique exists. The processing and display of this data base is different from the wake flow data, because the data base does not contain grey scale information. Consequently, we need to adopt and modify our image processing algorithms for dealing with the cloud-within-a-cloud problem.

III Nonlinear Optical Recording Media

Holographic work we have performed so far has used film as the recording medium. Film has excellent resolution and sensitivity properties, but its major drawback is that it can only be used once. To fully exploit the capabilities of our processing and display techniques reusable materials are needed. We are presently investigating other recording materials which will allow us not only to obtain real-time measurements, but used in a four-wave mixing configuration we can perform optical phase conjugation and real-time holography too. These materials are also ideally suitable for recording of scattered radiation in laser speckle velocimetry measurements. Presently available commercial crystals, however, are only obtainable in small sizes. Organic materials on the other hand may be synthesized into large formats and we are presently investigating new promising substances, including MNA and others. For this purpose a four-wave mixing configuration has been set-up this summer in a new laboratory, but no results are available yet.

Publications and Presentations

1. Holographic Display Devices, Invited Paper, Proceedings International Technical Conference/Europe in Geneva, April 18-22, 1983.
2. Quantitative Three-Dimensional Flow Visualization, Proceedings Third International Conference on Flow Visualization, Ann Arbor, Michigan, September 1983.

Personnel

Lambertus Hesselink Professor, Aeronautics/Astronautics and Electrical Engineering

John Pender Graduate student in Applied Physics

2.10 COHERENT ANTI-STOKES RAMAN SPECTROSCOPY (CARS)

Introduction

The objective of this aspect of the program has been to develop innovative laser spectroscopic techniques for supersonic and combustive turbulent flows. During the past three years we have successfully utilized the Coherent Anti-Stokes Raman Spectroscopic (CARS) technique to measure temperature and velocity in a supersonic jet flow. We have, in addition, used the same apparatus to measure density in the flow by an induced fluorescence technique. This latter measurement method led to a joint Applied Physics/Astronautics Ph.D. research program that culminated in the Ph.D. of Jim McDaniel. Most recently we have focused our work on experimental and theoretical studies on spatial resolution aspects of CARS spectroscopy, this effort culminating in the Ph.D. thesis of Eric Gustafson.

Scientific Merit

Cars spectroscopy has been increasingly used as a diagnostic probe for combustion and fluid flow studies. Our work on high resolution CARS in supersonic jets has led to a new understanding of the CARS process in cold expansion flows. We have demonstrated the highest resolution Raman spectra ever achieved. We have measured velocity and temperature to high accuracy in the flow, and we have completed a detailed theory for transit time broadened CARS in a supersonic flow.

The combination of high resolution laser sources and supersonic expansion cooled molecular flows has now been recognized as an important advance in laser spectroscopy.

Status Report

During the last year we have concluded our work on CARS spectroscopy with the complete of four manuscripts. Two works have been published on CARS spectroscopy in a supersonic expansion (see papers 1 and 2 listed at end of this section). The third paper, a theoretical study of the supersonic expansion presents, in addition to the theory of the jet,

usable numerical results for predicting the flowfield of the isentropic expansion zone of the jet (see paper 3). The fourth paper describes a safe and simple technique for doing CARS spectroscopy of dangerous gases (see paper 4).

In addition, we have completed and are preparing for publication new theoretical work on the problem of spatial resolution in four wave mixing. Because of the limited space available here and the large amount of work completed this year we will concentrate, in this report, on the four wave mixing calculations.

In recent years four wave mixing has become an important tool for spatially resolved combustion diagnostics. However, one of the principle stumbling blocks of this technique is the lack of a useful and easily determined resolved volume element. Toward answering this question we have undertaken a course of study at Stanford to determine the size and shape of the resolved volume element in crossed beam four wave mixing experiments.

There are several restrictions on the validity of these calculations. First, we have assumed Gaussian plane waves for the pump waves. This is not, in practice, a restriction because if the beams are crossed the overlap volume is small enough so that the pump beams diffract little in this volume. Second, we have assumed that diffraction of the generated wave may be neglected. This is certainly the case if the entire generated signal is collected. Third, we have assumed that the four waves satisfy the Bragg condition. Fourth, we have assumed that dispersion is insignificant. This is a valid assumption as long as the beams do not overlap over a distance large compared to the coherence length. On the whole the validity of the calculations is not compromised by these assumptions because in spatially resolved combustion diagnostics the technique is always implemented in a regime consistent with these assumptions.

The calculational program we followed consisted of the following steps. For given input frequencies, ω_1 , ω_2 and ω_3 , and angle between the generated wave \vec{k}_4 vector and $\vec{k}_1(\theta_1)$ we found the driving polarizations

consistent with the Bragg condition. These solutions consist of an infinite number of possible \bar{K}_2 and \bar{K}_3 directions lying on cones as shown in Fig. 1. The slowly varying part of the driving polarization defines contour surfaces that are ellipsoids whose major axes are determined by the spot sizes and the \bar{K} vectors. The driven wave equation for the generated field is determined for a driving polarization contained inside of a given ellipsoid and zero outside of the ellipsoid of volume V . The signal field is calculated from this driven wave equation and the total power in the signal wave is found by integrating over the transverse spatial extent of the signal wave intensity.

Figure 2 shows a typical plot of the signal for a given set of spot sizes the angle θ_1 between \bar{K}_1 and \bar{K}_4 and a particular orientation of \bar{K}_2 consistent with the Bragg condition as a function of the volume V contained by a sequence of larger and larger similar ellipsoids.

As Fig. 2 shows, the conversion efficiency increases monotonically as the driving polarization volume increases. In addition, as θ_2 increases, and the beam geometry becomes less planar, the conversion efficiency decreases. The resolved volume can now be defined as that volume for which 99% of the signal is generated. As the beam geometry moves away from the planar geometry toward geometries where the beams cross at steeper and steeper angles, the resolved volume decreases.

In conclusion, we have developed a rational and simple way to determine the approximate size and shape of the resolved volume in crossed beam four wave mixing experiments. We expect to publish this work before the end of the year.

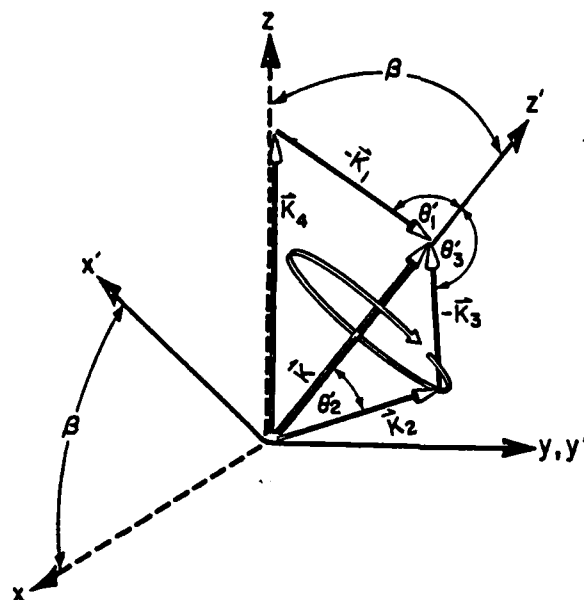


Fig. 1 For all beam geometries where $\vec{k}_2 - \vec{k}_3$ equals \vec{k} , the Bragg condition will be satisfied. θ'_2 is the aximuthal angle of \vec{k}_2 about z' .

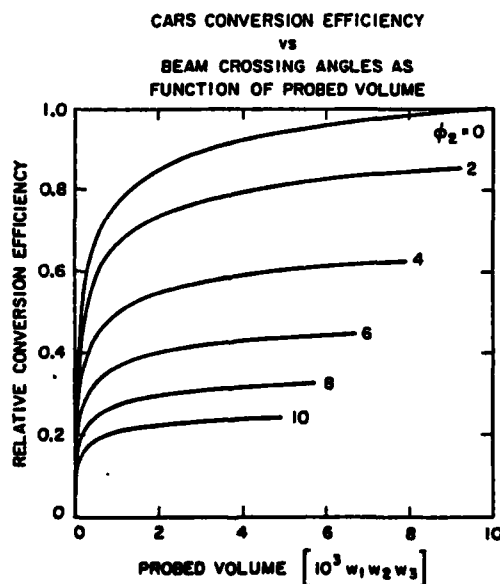


Fig. 2 The conversion efficiency for an angle of $\theta_1 = 30^\circ$ between the generated wave \vec{k}_4 and \vec{k}_1 for several angles θ'_2 . The spot sizes are $w_1 = w_2 = w_3 = 10 \mu\text{m}$ and the K vectors are $K_1 = 20,000 \text{ cm}^{-1}$, $K_2 = 19,000 \text{ cm}^{-1}$ and $K_3 = 18,000 \text{ cm}^{-1}$.

Publications and Presentations

Presentations

1. E. Gustafson, J. McDaniel and R.L. Byer, "Continuous Wave CARS Measurements in a Supersonic Jet," paper W01, CLEO Conference, June 1981, Washington, D.C.
2. R.L. Byer, M. Duncan, E. Gustafson, P. Oesterlin and F. Konig, "Pulsed and cw Molecular Beam CARS Spectroscopy," presented at the International Laser Spectroscopy Conference, July 1981, Jasper, Canada.

Publications

1. E.K. Gustafson and R.L. Byer, "High Resolution cw CARS Spectroscopy in a Supersonic Expansion," Laser Spectroscopy VI, Springer Series in Optical Sciences 1983.
2. "CARS Spectroscopy in a Supersonic Jet," E.K. Gustafson Ph.D. Dissertation, Stanford University, May 1983.
3. E.K. Gustafson, R.L. Byer and J.C. McDaniel, "Characterization of the Axisymmetric Supersonic Jet for Spectroscopic Applications," Journ. of Chem. Phys. (to be published).
4. E.K. Gustafson and R.L. Byer, "Coherent Anti-Stokes Raman Scattering from Small Volumes," Journ. of Chem. Phys. (to be published).

Personnel

Rober L. Byer	Professor and Chairman Applied Physics Department
Eris Gustafson	Graduate Student, Applied Physics (Ph.D. awarded in June 1983)
Jim McDaniel	Graduate Student, Aeronautical and Astronautics (Ph.D. awarded in December 1981).

2.11 COMPUTED ABSORPTION TOMOGRAPHY

Introduction

The imaging and potential benefits of laser tomography to combustion diagnostics were summarized in the original proposal. Discussions with researchers in combustion diagnostics and fluid flow visualization research have confirmed our original assumption that tomographic images are indeed very useful. During this reporting period we have continued our work to develop absorption tomography for imaging two-dimensional iodine vapor distributions in a plane.

Scientific Merit

The goal of our tomography effort is to apply tunable laser sources and tomographic image technology to the study of combusting flows. The interest stems from the potential for inferring the distributions of temperature, density and species concentration in a plane. The visualization of these parameters is very important for the understanding of complex conditions that occur in real combustion systems. A better knowledge of turbulence and combustion on more complex combustors should lead to improvements in the design of combustors for both improved efficiency and longer operational life.

Status Report

In the following, we discuss our current experimental set-up and present initial results.

Iodine is seeded into a slow nitrogen flow. By varying the temperature of the flow between -5°C and $+40^{\circ}\text{C}$, the saturated vapor pressure of iodine can be varied from 50 to 1300 microns which corresponds to absorption lengths from 700 cm^{-1} down to 24 cm^{-1} . Our flow system geometry allows us to vary the size of the iodine vapor column to investigate the resolution of our systems.

Ninety detectors are arranged on a 22 inch diameter circle, and the number of fans per revolution can be electronically varied from 45 to 360.

We have also implemented facilities for averaging the data to improve the signal-to-noise of the system. A diagram of the physical arrangement of the apparatus is shown in last year's report. We have replaced the mirror train used to direct the laser to the rotating mirror with a multimode fiber optic cable with excellent results.

Figure 1 is a tomogram of a 3.5 inch diameter I_2 cloud at 35°C. The tomogram is constructed from 180 fan/revolution data, and in the absence of averaging. The line cut horizontally through the center of the disk gives an estimate of the signal-to-noise in the reconstruction. The structure in the disk is a spatial variation of the iodine vapor concentration, and the fact that the iodine concentration was not uniform was verified by visually inspecting the fluorescence.

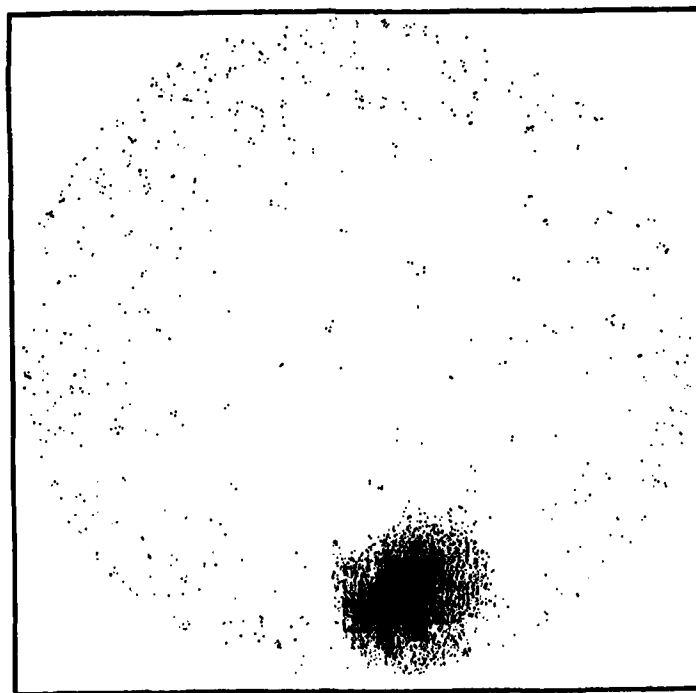


Fig. 1 Tomographic image of I_2 flow.

Similar data at other temperatures (for a 2 inch diameter source) was used to construct the plot of absorbance vs vapor pressure shown in Fig. 2. It is expected that refining the iodine injector and other experimental details will allow an improvement in the fit, and include data at lower temperatures.

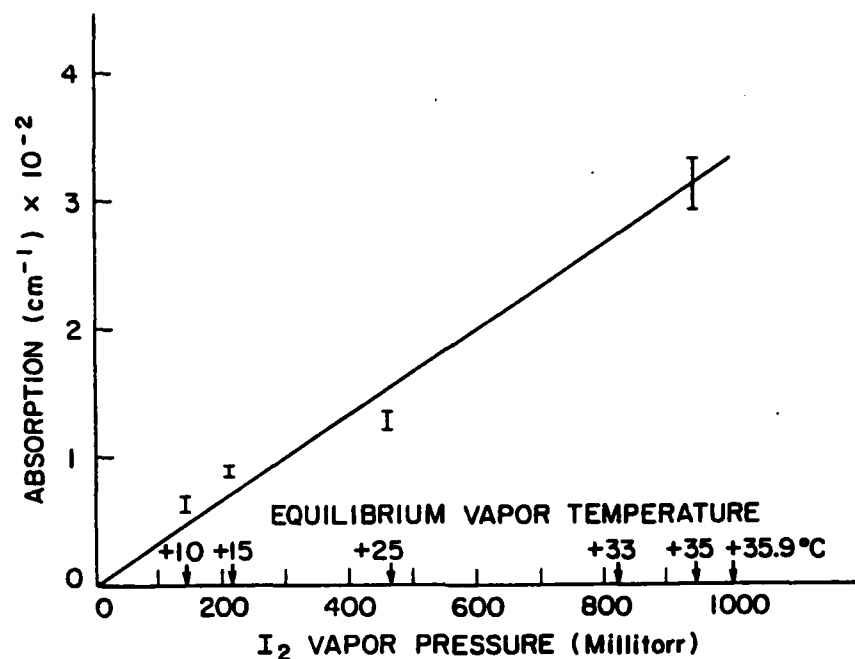


Fig. 2 Average laser absorption vs I₂ vapor pressure

In the future, we plan to employ a McKenna flat-flame burner, which has been borrowed from Sandia Laboratories, to allow imaging of the soot density on a flame with a rich fuel/air ratio.

Publications and Presentations

Publications

1. D.C. Wolfe and R.L. Byer, "Model Studies of Laser Absorption Computed Tomography for Remote Air Pollution Measurements," *Applied Optics* 21, 1165 (1982).

Presentation

1. R.L. Byer, "Laser Tomography for Combustion Diagnostics," General Motors Research Laboratory Colloquium, November 13, 1980.
2. K.E. Bennett, G.W. Faris and R.L. Byer, "Laser Computed Tomography Flow Diagnostics," presented at the Conference on Lasers and Electro-Optics, Baltimore, Md. May 1983.

Personnel

Robert L. Byer

Professor and Chairman
Applied Physics Department

Keith Bennett

Graduate Student, Applied Physics

Greg Farris

Graduate Student, Applied Physics

END

FILMED

1-85

DTIC